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Mr Tompkins Explores the Atom

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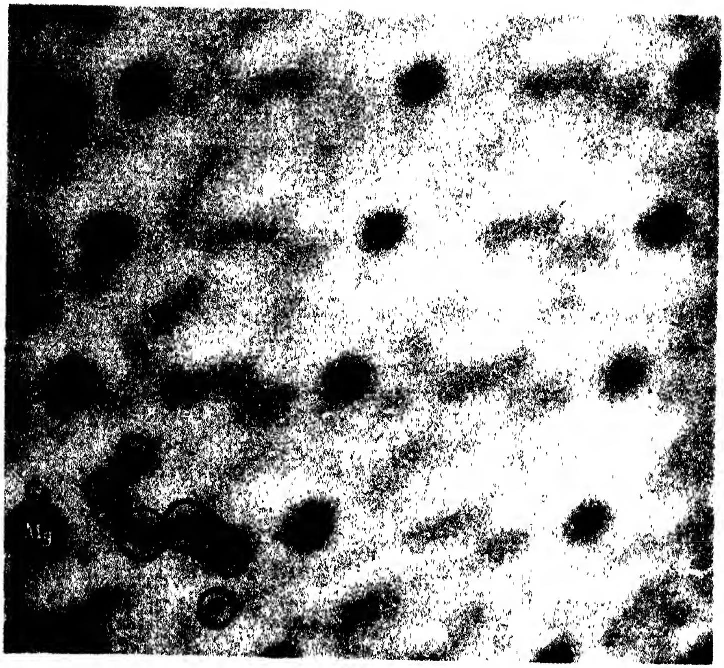
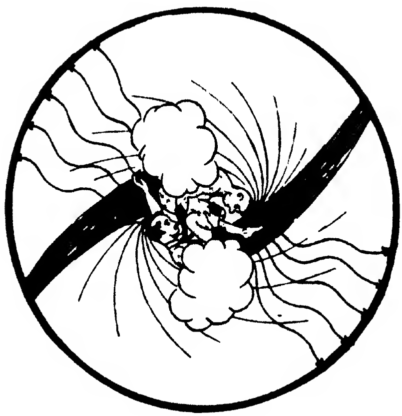


Bragg's photograph of atoms in a diopside crystal. The circles in the corner identify individual atoms of calcium, magnesium, silicon, and oxygen. Magnification about 100,000,000.

MR TOMPKINS EXPLORES THE ATOM

BY

G. GAMOW



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"Mr Tompkins, now safely married, no longer needs the dubious excitement of university lectures. Should, however, his father-in-law's expositions, now, no doubt, transferred to the domestic circle, include still further adventures, we hope Prof. Gamow will be at hand to report them."

J. A. CROWTHER
in *Nature*
April 13, 1940

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Preface

MANY strange things happen in dreams and probably among the strangest were the adventures experienced by a certain Mr Tompkins. He is just an ordinary person, a bank employee to be exact, who ventured to attend several semi-popular lectures on such basic problems of modern physics as relativity and the quantum theory. The startling statements he heard at the lectures, one apparently more paradoxical than the next, made such a deep impression on our hero's mind that his sleep was often disturbed by the craziest of nightmares related, if sometimes rather distantly, to what the professor had said. Mr Tompkins found himself riding a bicycle on the shrinking streets of a weird relativistic city, and hunting on an elephant in a quantum jungle only to be attacked by the tiger from all sides at once, and in other nerve-racking predicaments. It is hard to say whether Mr Tompkins really got anything out of his unusual adventures beside his happy marriage to the professor's daughter Maud and his present dubious privilege of being exposed to his father-in-law's lectures morning, noon and night. The professor seems to feel it his duty to open the eyes of his ignorant son-in-law to the wonders of modern physics and never misses a chance to enlighten Mr Tompkins on the structure of matter and to make him feel at home among such phenomena as saturated electronic shells, nuclear potential barriers, annihilation of matter, etc.

The following represents a complete and true account of the professor's efforts, and it is up to the reader to decide whether or not he has at least partially succeeded in his task.

* * * * *

When the manuscript of the present volume was completed, the

author was very perturbed to realize that it would be practically impossible to get in touch with Mr John Hookham, creator of Mr Tompkins' facial features, now busy in England with more important matters. Therefore, difficult as it was, the author made up his mind to illustrate the volume with his own hand. Not being an artist, he borrowed freely from every source available, running the gamut from Botticelli's paintings to the comic sections of the Sunday papers. The pictures that have resulted from this bold effort may look somewhat crazy, but after all the stories themselves are rather crazy too.

In conclusion the author considers it a pleasant duty to express his gratitude to Mr Ronald Mansbridge, of the Cambridge University Press and The Macmillan Company, without whose encouragement and helpful advice preparation of this volume would hardly have been possible.

G. GAMOW

The George Washington University
September 1942.

First Dream

MAXWELL'S DEMON

"DO YOU really think this system will work?" asked Maud, raising her eyes reluctantly from a fashion magazine. "Father always says there can't be any such thing as a sure-fire gambling system."

"But look here, Maud," answered Mr Tompkins, showing her the article he had been studying for the last half hour.[1] "I don't know about other systems, but this one is based on pure and simple mathematics, and I really don't see how it could possibly go wrong. All you have to do is to write down three figures

1, 2, 3

on a piece of paper, and follow a few simple rules given here."

"Well, let's try it out," suggested Maud, beginning to be interested. "What are the rules?"

"Suppose you follow the example given in the article. That's probably the best way to learn them. As illustration, they have used a roulette game in which you place your money on red or black, which is the same as betting heads or tails on the flip of a coin. I write down

1, 2, 3

and the rule is that my bet must always be the sum of the outside figures in the series. So I take one plus three, which is four, chips and put them, let's say, on red. If I win, I cross out the figures 1 and 3 and my next bet will be the remaining figure 2. If I lose, I add the amount lost to the end of the series and apply the same rule to find my next bet. Well, suppose the ball stops on black and the croupier rakes in

[1] "Esquire", January 1940.

FIRST DREAM

"But you must *win this time!"*

my four chips. Then my new series will be

1, 2, 3, 4

and my next bet one plus four, which is five. Suppose I lose a second time. The article says I must keep on in the same way, adding the figure 5 at the end of the series and putting six chips on the table."

"But you *must* win this time!" cried Maud, getting quite excited. "You can't keep on losing."

"Not necessarily," said Mr Tompkins. "When I was a boy I used to flip pennies with my friends, and believe it or not, I once saw heads come up ten times in a row. But let's suppose, as this article does, that I win this time. Then I collect twelve chips, but I am still out three chips compared with my original stake. Following the rules, I must cross out the figures 1 and 5, and my series now reads

$\cancel{1}$, 2, 3, 4, $\cancel{5}$

My next bet must be two plus four, or six chips again."

"It says here you have lost again," sighed Maud, reading over her husband's shoulder. "That means you have to add six to the series and bet eight chips next time. Isn't that so?"

"Yes, that's right, but I lose again. My series is now

$\cancel{1}$, 2, 3, 4, $\cancel{5}$, 6, 8

and I have to bet ten this time. It wins. I cross out the figures 2 and 8 and my next bet is three plus six which is nine. But I lose again."

"It's a bad example," said Maud, pouting. "So far, you've lost three times and only won once. It's not fair!"

"Never mind, never mind," said Mr Tompkins with the quiet confidence of a magician. "We'll win all right at the end of the cycle. I lost nine chips on the last spin, so I'll add this figure to the series to make it

$\cancel{1}$, $\cancel{2}$, 3, 4, $\cancel{5}$, 6, $\cancel{8}$, 9

and bet twelve chips. I win this time, so I cross out the figures 3 and 9

and bet the sum of the remaining two, or ten chips. The second successive win completes the cycle as all the figures are now crossed out. And I am six chips up, in spite of the fact that I won only four times and lost five!"

"Are you sure you are six chips up?" asked Maud doubtfully.

"Quite sure. You see the system is arranged in such a way that, whenever the cycle is complete, you are always six chips up. You can prove it by simple arithmetic, and that's why I say this system is mathematical and can't fail. If you don't believe it, take a piece of paper and check it yourself."

"All right. I'll take your word for it that that's the way it works out," said Maud thoughtfully, "but, of course, six chips aren't very much to win."

"Yes they are, if you are sure of winning them at the end of each cycle. You can repeat the procedure over and over again, beginning each time with 1, 2, 3, and making as much money as you want. Isn't it *grand?"*

"Wonderful!" exclaimed Maud. "Then you can drop your work at the bank, we can move into a better house, and I saw a darling mink coat in a shop window today. It only cost . . ."

"Of course we'll buy it, but first we had better get to Monte Carlo quickly. A lot of other people must have read this article, and it would be too bad to get there only to find some other fellow had beaten us to it and put the Casino into bankruptcy."

"I'll ring up the air line," suggested Maud, "and find out when the next plane leaves."

"What's all the hurry about?" said a familiar voice in the hall. Maud's father came into the room and looked at the excited pair in surprise.

"We're leaving for Monte Carlo on the first plane and we're going to come home very rich," said Mr Tompkins, rising to greet the professor.

"Oh, I see," smiled the latter, making himself comfortable in an old-fashioned armchair near the fireplace. "You have a new gambling system?"

"But this time it's a real one, Father!" protested Maud, her hand still on the phone.

"Yes," added Mr Tompkins, handing the professor the magazine. "This one can't miss."

"Can't it?" said the professor with a smile. "Well, let's see." After a short inspection of the article, he went on, "The distinguishing feature of this system is that the rule governing the amount of your bets calls for you to raise your bet after each loss and, on the other hand, to lower your bet after each win. So, if you should win and lose alternately and with complete regularity, your capital would oscillate up and down, each increase being, however, slightly larger than the previous decrease. In such a case you would, of course, become a millionaire in no time. But as you no doubt understand, such regularity usually does not occur. As a matter of fact, the probability of such a regularly alternating series is just as small as the probability of an equal number of straight wins. So we must see what happens if you have a sequence of several successive wins or losses. If you get what gamblers call a streak of luck, the rule forces you to lower, or at least not to raise, your bet after each win, so your total winnings will not be very high. On the other hand, as you must raise your bet after each loss, a streak of bad luck will be more catastrophic and may throw you out of the game. You can now see that the curve representing the variations in your capital will consist of several slowly rising portions interrupted

by very sharp drops. At the beginning of the game, it is likely that you will get on to the long, slowly rising part of the curve and will enjoy for a while the pleasant feeling of watching your money slowly but surely increasing. However, if you go on long enough, in the hope of larger and larger profit, you will come unexpectedly to the sharp drop which might be deep enough to make you bet and lose your last penny. One can show, in a quite general way, that with this or any other system, the probability that the curve will reach the double mark is equal to that of reaching zero. In other words, the chances of finally winning are exactly the same as if you put all your money on red or black and double your capital or lose everything on just one spin of the wheel. All that such a system can do is to prolong the game and give you more fun for the money. But if that is all you want to do, you don't have to make it so complicated. There are thirty-six numbers on a roulette wheel, you know, and there is nothing to keep you from covering every number but one. Then the chances are thirty-five out of thirty-six that you will win and that the bank will pay you one chip more than the thirty-five you bet. However, about once in thirty-six spins the ball will stop on the particular number you chose not to cover with a chip, and you will lose all thirty-five. Play this way long enough and the curve of your fluctuating capital will look exactly like the curve you will get by following this magazine's system.

"Of course I have been assuming right along that the bank is taking no cut. As a matter of fact, every roulette wheel I have seen has a zero, and often a double zero as well, which raises the odds against the player. Regardless of the system he uses, therefore, the gambler's money gradually leaks from his pocket to the proprietor's."

"You mean to say," said Mr Tompkins dejectedly, "that there is no such thing as a good gambling system, and that there is no possible

way of winning money without risking the slightly higher probability of losing it?"

"That is precisely what I mean," said the professor. "What is more, what I have said applies not only to such comparatively unimportant problems as games of chance, but to a great variety of physical phenomena which, at first sight, seem to have nothing to do with the laws of probability. For that matter, if you could devise a system for beating the laws of chance, there are much more exciting things than winning money one could do with it. One could build cars that ran without gasoline, factories that could be operated without coal and plenty of other fantastic things."

"I've read something somewhere about such hypothetical machines—perpetual motion machines, I believe they are called," said Mr Tompkins. "If I remember correctly, machines planned to run without fuel are considered impossible because one cannot manufacture energy out of nothing. Anyway, such machines have no connection with gambling."

"You are quite right, my boy," agreed the professor, pleased that his son-in-law knew something at least about physics. "This kind of perpetual motion, 'perpetual motion machines of the first type' as they are called, cannot exist because they would be contrary to the Law of the Conservation of Energy. However the fuel-less machines I have in mind are of a rather different type and are usually known as 'perpetual motion machines of the second type'. They are not designed to create energy out of nothing, but to extract energy from surrounding heat reservoirs in the earth, sea or air. For instance, you can imagine a steamship in whose boilers steam was gotten up, not by burning coal but by extracting heat from the surrounding water. In fact, if it were possible to force heat to flow away from cold toward greater heat, in-

stead of the other way round, one could construct a system for pumping in sea-water, depriving it of its heat content, and disposing of the residue blocks of ice overboard. When a gallon of cold water freezes into ice, it gives off enough heat to raise another gallon of cold water almost to the boiling point. By pumping through several gallons of sea-water per minute, one could easily collect enough heat to run a good-sized engine. For all practical purposes, such a perpetual motion machine of the second type would be just as good as the kind designed to create energy out of nothing. With engines like this to do the work, everyone in the world could live as carefree an existence as a man with an unbeatable roulette system. Unfortunately they are equally impossible as they both violate the laws of probability in the same way."

"I admit that trying to extract heat out of sea-water to raise steam in a ship's boilers is a crazy idea," said Mr Tompkins. "However, I fail to see any connection between that problem and the laws of chance. Surely, you are not suggesting that dice and roulette wheels should be used as moving parts in these fuel-less machines. Or are you?"

"Of course not!" laughed the professor. "At least I don't believe even the craziest perpetual motion inventor has made that suggestion yet. The point is that heat processes themselves are very similar in their nature to games of dice, and to hope that heat will flow from the colder body into the hotter one is like hoping that money will flow from the casino's bank into your pocket."

"You mean that the bank is cold and my pocket hot?" asked Mr Tompkins, by now completely befuddled.

"In a way, yes," answered the professor. "If you hadn't missed my lecture last week, you would know that heat is nothing but the rapid irregular movement of innumerable particles, known as atoms and molecules, of which all material bodies are constituted. The more vio-

lent this molecular motion is, the warmer the body appears to us. As this molecular motion is quite irregular, it is subject to the laws of chance, and it is easy to show that the most probable state of a system made up of a large number of particles will correspond to a more or less uniform distribution among all of them of the total available energy. If one part of the material body is heated, that is if the molecules in this region begin to move faster, one would expect that, through a large number of accidental collisions, this excess energy would soon be distributed evenly among all the remaining particles. However, as the collisions are purely accidental, there is also the possibility that, merely by chance, a certain group of particles may collect the larger part of the available energy at the expense of the others. This spontaneous concentration of thermal energy in one particular part of the body would correspond to the flow of heat against the temperature gradient, and is not excluded in principle. However, if one tries to calculate the relative probability of such a spontaneous heat concentration occurring, one gets such small numerical values that the phenomenon can be labeled as practically impossible."

"Oh, I see it now," said Mr Tompkins. "You mean that these perpetual motion machines of the second kind might work once in a while, but that the chances of that happening are as slight as they are of throwing a seven a hundred times in a row in a dice game."

"The odds are much smaller than that," said the professor. "In fact, the probabilities of gambling successfully against nature are so slight that it is difficult to find words to describe them. For instance, I can work out the chances of all the air in this room collecting spontaneously under the table, leaving an absolute vacuum everywhere else. The number of dice you would throw at one time would be equivalent to the number of air molecules in the room, so I must know how many there

are. One cubic centimeter of air at atmospheric pressure, I remember, contains a number of molecules described by a figure of twenty digits, so the air molecules in the whole room must total a number with some twenty-seven digits. The space under the table is about one per cent of the volume of the room, and the chances of any given molecule being under the table and not somewhere else are, therefore, one in a hundred. So, to work out the chances of all of them being under the table at once, I must multiply one hundredth by one hundredth and so on, for each molecule in the room. My result will be a decimal beginning with fifty-four naughts."

"Phew . . . !" sighed Mr Tompkins, "I certainly wouldn't bet on those odds! But doesn't all this mean that deviations from equipartition are simply impossible?"

"Yes," agreed the professor. "You can take it as a fact that we won't suffocate because all the air is under the table, and for that matter that the liquid won't start boiling by itself in your high-ball glass. But if you consider much smaller areas, containing much smaller numbers of our dice-molecules, deviations from statistical distribution become much more probable. In this very room, for instance, air molecules habitually group themselves somewhat more densely at certain points, giving rise to minute inhomogeneities, called statistical fluctuations of destiny. When the sun's light passes through terrestrial atmosphere, such inhomogeneities cause the scattering of the blue rays of spectrum, and give to the sky its familiar color. Were these fluctuations of destiny not present, the sky would always be quite black, and the stars would be clearly visible in full daylight. Also the slightly opalescent light liquids get when they are raised close to the boiling point is explained by these same fluctuations of density produced by the irregularity of

molecular motion. But on a large scale, such fluctuations are so extremely improbable that we would watch for billions of years without seeing one."

"But there is still a chance of the unusual happening right now in this very room," insisted Mr Tompkins. "Isn't there?"

"Yes, of course there is, and it would be unreasonable to insist that a bowl of soup couldn't spill itself all over the table cloth because half of its molecules had accidentally received thermal velocities in the same direction."

"Why that very thing happened only yesterday," chimed in Maud, taking an interest now she had finished her magazine. "The soup spilled and the maid said she hadn't even touched the table."

The professor chuckled. "In this particular case," he said, "I suspect the maid, rather than Maxwell's Demon, was to blame."

"Maxwell's Demon?" repeated Mr Tompkins, surprised. "I should think scientists would be the last people to get notions about demons and such."

"Well, we don't take him very seriously," said the professor. "Clerk Maxwell, the famous physicist, was responsible for introducing the notion of such a statistical demon simply as a figure of speech. He used this notion to illustrate discussions on the phenomena of heat. Maxwell's Demon is supposed to be rather a fast fellow, and capable of changing the direction of every single molecule in any way you prescribe. If there really were such a demon, heat could be made to flow against temperature, and the fundamental law of thermodynamics, the *principle of increasing entropy,* wouldn't be worth a nickel."

"Entropy?" repeated Mr Tompkins. "I've heard that word before. One of my colleagues once gave a party, and after a few drinks, some

chemistry students he'd invited started singing—

> '*In*creases, *de*creases
> *De*creases, *in*creases
> What the hell do we care
> What the entropy does?' [2]

to the tune of 'Ach du lieber Augustine'. What is the entropy anyway?"

"It's not difficult to explain. 'Entropy' is simply a term used to describe the degree of disorder of molecular motion in any given physical body or system of bodies. The numerous irregular collisions between the molecules tend always to increase the entropy, as an absolute disorder is the most probable state of any statistical ensemble. However, if Maxwell's Demon could be put to work, he would soon put some order into the movement of the molecules the way a good sheep dog rounds up and steers a flock of sheep, and the entropy would begin to decrease. I should also tell you that according to the so-called H-theorem Lüdwig Boltzmann introduced to science . . ."

Apparently forgetting he was talking to a man who knew practically nothing about physics and not to a class of advanced students, the professor rambled on, using such monstrous terms as "generalized parameters" and "quasi-ergodic systems", thinking he was making the fundamental laws of thermodynamics and their relation to Gibbs' form of statistical mechanics crystal clear. Mr Tompkins was used to his father-in-law talking over his head, so he sipped his Scotch and soda philosophically and tried to look intelligent. But all these highlights of statistical physics were definitely too much for Maud, curled up in her

[2] Stephen Brunauer, "The Adsorption of Gases and Vapors." Princeton University Press. 1943.

chair and struggling to keep her eyes open. To throw off her drowsiness she decided to go and see how dinner was getting along.

"Does madam desire something?" inquired a tall, elegantly dressed butler, bowing as she came into the dining room.

"No, just go on with your work," she said, wondering why on earth he was there. It seemed particularly odd as they had never had a butler and certainly could not afford one. The man was tall and lean with an olive skin, long, pointed nose, and greenish eyes which seemed to burn with a strange, intense glow. Shivers ran up and down Maud's spine when she noticed the two symmetrical lumps half hidden by the black hair above his forehead.

"Either I'm dreaming," she thought, "or this is Mephistopheles himself, straight out of grand opera."

"Did my husband hire you?" she asked aloud, just for something to say.

"Not exactly," answered the strange butler, giving a last artistic touch to the dinner table. "As a matter of fact, I came here of my own accord to show your distinguished father I am not the myth he believes me to be. Allow me to introduce myself. I am Maxwell's Demon."

"Oh!" breathed Maud with relief, "Then you probably aren't wicked, like other demons, and have no intention of hurting anybody."

"Of course not," said the Demon with a broad smile, "But I like to play practical jokes and I'm about to play one on your father."

"What are you going to do?" asked Maud, still not quite reassured.

"Just show him that, if I choose, the law of increasing entropy can be broken. And to convince you it can be done, I would appreciate the honor of your company. It is not at all dangerous, I assure you."

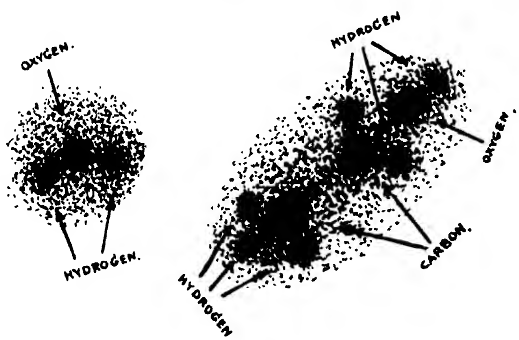
At these words, Maud felt the strong grip of the Demon's hand on her elbow, and everything around her suddenly went crazy. All the

familiar objects in her dining room began to grow with terrific speed, and she got a last glimpse of the back of a chair covering the whole horizon. When things finally quieted down, she found herself floating in the air supported by her companion. Foggy-looking spheres, about the size of tennis balls, were whizzing by in all directions, but Maxwell's Demon cleverly kept them from colliding with any of the dangerous looking things. Looking down, Maud saw what looked like a fishing boat, heaped to the gunwales with quivering, glistening fish.

They were not fish, however, but a countless number of foggy balls, very like those flying past them in the air. The Demon led her closer until she seemed surrounded by a sea of coarse gruel which was moving and working in a patternless way. Balls were boiling to the surface and others seemed to be sucked down. Occasionally one would come to the surface with such speed it would tear off into space, or one of the balls flying through the air would dive into the gruel and disappear under thousands of other balls. Looking at the gruel more closely, Maud discovered that the balls were really of two different kinds. If most looked like tennis balls, the larger and more elongated ones were shaped more like American footballs. All of them were semi-transparent and seemed to have a complicated internal structure which Maud could not make out.

"Where are we?" gasped Maud. "Is this what hell looks like?"

"No," smiled the Demon, "Nothing as fantastic as that. We are simply taking a close look at a very small portion of the liquid surface of the highball which is succeeding in keeping your husband awake while your father expounds quasi-ergodic systems. All these balls are molecules. The smaller round ones are water molecules and the larger,



longer ones are molecules of alcohol. If you care to work out the proportion between their number, you can find out just how strong a drink your husband poured himself."

"*Very* interesting," said Maud, as sternly as she dared. "But what are those things over there that look like a couple of whales playing in the water. They couldn't be atomic whales, or could they?"

The demon looked where Maud pointed. "No, they are hardly whales," he said. "As a matter of fact, they are a couple of very fine fragments of burned barley, the ingredient which gives whisky its particular flavor and color. Each fragment is made up of millions and millions of complex organic molecules and is comparatively large and heavy. You see them bouncing around because of the action of impacts they receive from the water and alcohol molecules animated by thermal motion. It was the study of such intermediate-sized particles, small enough to be influenced by molecular motion but still large enough to be seen through a strong microscope, which gave scientists their first direct proof of the kinetic theory of heat. By measuring the intensity of the tarantella-like dance executed by such minute particles suspended in liquids, their Brownian motion as it is usually called, physicists were able to get direct information on the energy of molecular motion."

Again the Demon guided her through the air until they came to an enormous wall made of numberless water molecules fitted neatly and closely together like bricks.

"How very impressive!" cried Maud. "That's just the background I've been looking for for a portrait I'm painting. What is this beautiful building, anyway?"

"Why, this is part of an ice crystal, one of many in the ice cube in your husband's glass," said the Demon. "And now, if you will excuse

me, it is time for me to start my practical joke on the old, self-assured professor."

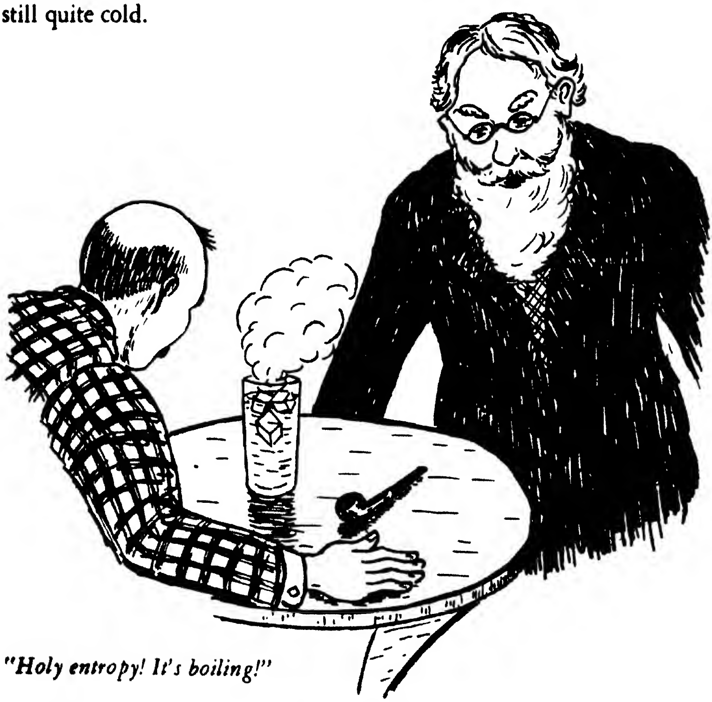
So saying, Maxwell's Demon left Maud perched on the edge of the ice crystal, like an unhappy mountain climber, and set about his work. Armed with an instrument like a tennis racquet, he was swatting the molecules around him. Darting here and there, he was always in time to swat any stubborn molecule which persisted in going in the wrong direction. In spite of the apparent danger of her position, Maud could not help admiring his wonderful speed and accuracy, and found herself cheering with excitement whenever he succeeded in deflecting a particularly fast and difficult molecule. Compared with the exhibition she was witnessing, champion tennis players she had seen looked like hopeless duffers. In a few minutes, the results of the Demon's work were quite apparent. Now, although one part of the liquid surface was covered by very slowly moving, quiet molecules, the part directly under her feet was more furiously agitated than ever. The number of molecules escaping from the surface in the process of evaporation was increasing rapidly. They were now escaping in groups of thousands together, tearing through the surface as giant bubbles. Then a cloud of steam covered Maud's whole field of vision and she could get only occasional glimpses of the whizzing racquet or the tail of the Demon's dress suit among the masses of maddened molecules. Finally the molecules in her ice crystal perch gave way and she fell into the heavy clouds of vapor beneath . . .

When the clouds cleared, Maud found herself sitting in the same chair she was sitting in before she went into the dining room.

"Holy entropy!" her father shouted, staring bewildered at Mr Tompkins' highball, "It's boiling!"

The liquid in the glass was covered with violently bursting bubbles,

and a thin cloud of steam was rising slowly toward the ceiling. It was particularly odd, however, that the drink was boiling only in a comparatively small area around the ice cube. The rest of the drink was still quite cold.



"Holy entropy! It's boiling!"

"Think of it!" went on the professor in an awed, trembling voice. "Here I was telling you about statistical fluctuations in the law of entropy when we actually see one! By some incredible chance, possibly for the first time since the earth began, the faster molecules have all

grouped themselves accidentally on one part of the surface of the water and the water has begun to boil by itself! In the billions of years to come, we will still, probably, be the only people who ever had the chance to observe this extraordinary phenomenon." He watched the drink, which was now slowly cooling down. "What a stroke of luck!" he breathed happily.

Maud smiled but said nothing. She did not care to argue with her father, but this time she felt sure she knew better than he.

Second Dream

THE GAY TRIBE OF ELECTRONS

A FEW days later, while finishing his dinner, Mr Tompkins remembered that it was the night of the professor's lecture on the structure of the atom, which he had promised to attend. But he was so fed up with his father-in-law's interminable expositions that he decided to forget the lecture and spend a comfortable evening at home. However, just as he was getting settled with his book, Maud cut off this avenue of escape by looking at the clock and remarking, gently but firmly, that it was almost time for him to leave. So, half an hour later, he found himself on a hard wooden bench in the university auditorium together with a crowd of eager young students.

"Ladies and gentlemen," began the professor, looking at them gravely over his spectacles, "In my last lecture I promised to give you more details concerning the internal structure of the atom, and to explain how the peculiar features of this structure account for its physical and chemical properties. You know, of course, that atoms are no longer considered as elementary indivisible constituent parts of matter, and that this role has passed now to much smaller particles such as electrons, protons, etc.

"The idea of elementary constituent particles of matter, representing the last possible step in divisibility of material bodies, dates back to the ancient Greek philosopher DEMOCRITUS who lived in the fourth century B.C. Meditating about the hidden nature of things, Democritus came to the problem of the structure of matter and was faced with the question whether or not it can exist in infinitely small portions. Since it was not customary at this epoch to solve any problem by any other method than

that of pure thinking, and since, in any case, the question was at that time beyond any possible attack by experimental methods, Democritus searched for the correct answer in the depths of his own mind. On the basis of some obscure philosophical considerations he finally came to the conclusion that it is 'unthinkable' that matter could be divided into smaller and smaller parts without any limit, and that one must assume the existence of 'the smallest particles which cannot be divided any more'. He called such particles 'atoms', which, as you probably know, means 'indivisibles' in Greek.

"I do not want to minimize the great contribution of Democritus to the progress of natural science, but it is worth keeping in mind that besides Democritus and his followers, there was undoubtedly another school of Greek philosophy the adherents of which maintained that the process of divisibility of matter *could* be carried beyond any limit. Thus, independent of the character of the answer which had to be given in the future by exact science, the philosophy of ancient Greece was well secured with an honorable place in the history of physics. At the time of Democritus, and for centuries later, the existence of such indivisible portions of matter represented a purely philosophical hypothesis, and it was only in the nineteenth century that scientists decided that they had finally found these indivisible building-stones of matter which were foretold by the old Greek philosopher more than two thousand years ago.

"In fact, in the year 1808 an English chemist, JOHN DALTON, showed that the relative proportions . . ."

Almost from the beginning of the lecture Mr Tompkins had felt an irresistible urge to close his eyes and doze through the rest of the lecture, and it was only the academic hardness of the bench that kept him from doing so. However, Dalton's ideas concerning the law of "rela-

tive proportions" proved the last straw, and the hushed auditorium was soon permeated by a gentle wheeze coming from the corner where Mr Tompkins was sitting.

*   *   *   *   *

When Mr Tompkins dropped off to sleep, the discomfort of the uncompromising bench seemed to melt into the pleasant sensation of floating on air, and opening his eyes he was surprised to find himself dashing through space at what he considered a pretty reckless speed. Looking around he saw that he was not alone on this fantastic trip. Near him a number of vague, misty forms were swooping around a large heavy-looking object in the middle of the crowd. These strange beings were traveling in pairs, gaily chasing each other along circular and elliptic tracks. Suddenly Mr Tompkins felt very lonely because he realized that he was the only one of the whole group who had no playmate.

"Why didn't I bring Maud along with me?" Mr Tompkins wondered gloomily. "We could have had a wonderful time with this happy-go-lucky crowd." The track he was moving along was outside all the others, and while he wanted very much to join the party, the uncomfortable feeling of being odd man out kept him from doing so. However, when one of the electrons (for by now Mr Tompkins realized he had miraculously joined the electronic community of an atom) was passing close bv on its elongated track, he decided to complain about the situation.

"Why haven't *I* got anyone to play with?" he shouted across.

"Because this is an odd atom, and you are the valency electr-o-o-on . . ." called the electron as it turned and plunged back into the dancing crowd.

"Valency electrons live alone or find companions in other atoms," squeaked the high pitched soprano of another electron rushing past him.

"If you want a partner fair,
Jump into chlorine and find one there,"

chanted another mockingly.

"I see you are quite new here, my son, and very lonely," said a friendly voice above him, and raising his eyes Mr Tompkins saw the stout figure of a monk clothed in a brown tunic.

"I am Father Paulini," went on the monk, moving along the track with Mr Tompkins, "and it is my mission in life to keep watch over the morals and social life of electrons in atoms and elsewhere. It is my duty to keep these playful electrons properly distributed among the different quantum cells of the beautiful atomic structures erected by our great architect Niels Bohr. To keep order and to preserve the proprieties, I never permit more than two electrons to follow the same track; a *ménage à trois* always gives a lot of trouble, you know. Thus electrons are always grouped in pairs of opposite 'spin' and no intruder is permitted if the cell is already occupied by a couple. It is a good rule, and I may add that not a single electron has yet broken my commandment."

"Maybe it *is* a good rule," objected Mr Tompkins, "but it is rather inconvenient for me at the moment."

"I see it is," smiled the monk, "but it is just your bad luck, being a valency electron in an odd atom. The sodium atom to which you belong is entitled by the electric charge of its nucleus (that big dark mass you see in the center) to hold eleven electrons altogether. Well, unfortunately for you, eleven is an odd number, hardly an unusual circumstance when you consider that exactly one half of all numbers are odd, and only the other half even. Thus, as the latecomer you will have to be alone for a while at least."

"You mean there is a chance that I can get in later?" asked Mr Tompkins eagerly. "Kicking one of the oldtimers out, for example?"

"It isn't exactly done," said the monk wagging a plump finger at him, "but, of course, there is always a chance that some of the inner circle members will be thrown out by an external disturbance, leaving an empty place. However, I wouldn't count on it much, if I were you."

"They told me I'd be better off if I moved into chlorine," said Mr Tompkins, discouraged by Father Paulini's words. "Can you tell me how to do that?"

"Young man, young man!" exclaimed the monk sorrowfully, "why are you so insistent on finding company? Why can't you appreciate solitude and this Heaven-sent opportunity to contemplate your soul in peace? Why must even electrons lean always to the worldly life? However, if you insist on companionship, I will help you get your wish. If you look where I'm pointing, you will see a chlorine atom approaching us, and even at this distance you can see an unoccupied spot where you would most certainly be welcomed. The empty spot is in the outer group of electrons, the so-called 'M-shell', which is supposed to be made up of eight electrons grouped in four pairs. But, as you see, there are four electrons spinning in one direction and only three in the other, with one place vacant. The inner shells, known as 'K' and 'L', are completely filled up, and the atom will be glad to get you and have its outer shell complete. When the two atoms get close together, just jump over, as valency electrons usually do. And may peace be with you, my son!" With these words the impressive figure of the electron priest suddenly faded into thin air.

Feeling considerably more cheerful, Mr Tompkins gathered his strength for a neckbreaking jump into the orbit of the passing chlorine atom. To his surprise he leapt over with an easy grace and found himself in the congenial surroundings of the members of the chlorine M-shell.

"It was delightful of you to join us!" called his new partner of opposite spin, gliding gracefully along the track. "Now no one can say that our community is not complete. Now we shall all have fun together!"

Mr Tompkins agreed that it really was fun—lots of fun—but one little worry kept stealing into his mind. "How am I going to explain this to Maud when I see her again?" he thought rather guiltily, but not for long. "Surely she won't mind," he decided. "After all, these are only electrons."

"Why doesn't that atom you've left go away now?" asked his companion with a pout. "Does it still hope to get you back?"

And, as a matter of fact, the sodium atom, with its valency electron gone, *was* sticking closely to the chlorine one as if in the hope that Mr Tompkins would change his mind and jump back to his lonely track.

"Well how do you like that!" said Mr Tompkins angrily, frowning at the atom which had first received him so coldly. "There's a dog in the manger for you!"

"Oh they always do that," said a more experienced member of the M-shell. "I understand it is not so much the electronic community of the sodium atom which wants you back as the sodium nucleus itself. There is almost always some disagreement between the central nucleus and its electronic escort: the nucleus wants as many electrons around it as it can possibly hold with its electric charge, whereas the electrons themselves prefer to be only enough in number to make the shells complete. There are only a few atomic species, the so-called *rare gases*, or *noble gases* as the German chemists call them, in which the desire of the ruling nucleus and the subordinate electrons are in full harmony. Such atoms as helium, neon and argon, for example, are quite satisfied with themselves and neither expel their number nor invite new ones. They

are chemically inert, and keep away from all other atoms. But in all other atoms electronic communities are always ready to change their membership. In the sodium atom, which was your former home, the nucleus is entitled by its electric charge to one more electron than is necessary for harmony in the shells. On the other hand, in our atom the normal contingent of electrons is not enough for complete harmony, and thus we welcome your arrival, in spite of the fact that your presence overloads our nucleus. But as long as you stay here, our atom is not neutral any more, and has an extra electric charge. Thus the sodium atom which you left stands by, held by the force of electric attraction. I once heard our great priest, Father Paulini, say that such atomic communities, with extra electrons or electrons missing, are called negative and positive 'ions'. He also uses the word 'molecule' for groups of two or more atoms bound together by electric force. This particular combination of sodium and chlorine atoms he calls a molecule of 'table salt', whatever that may be."

"Do you mean to tell me you don't know what table salt is?" said Mr Tompkins, forgetting to whom he was talking. "Why that's what you put on your scrambled eggs at breakfast."

"What are 'scram bulldeggs' and what is 'break-fust'?" asked the intrigued electron. Mr Tompkins sputtered and then realized the futility of trying to explain to his companions even the simplest details of the lives of human beings. "That's why I don't get more out of their talk about valency and complete shells," he told himself, deciding to enjoy his visit to this fantastic world without worrying about understanding it. But it was not so easy to get away from the talkative electron who evidently had a great desire to pass on all the knowledge collected during a long electronic life.

"You must not think," he continued, "that the binding of atoms into

molecules is always accomplished by one valency electron alone. There are atoms, like oxygen for example, which need two more electrons to complete their shells, and there are also atoms which need three electrons and even more. On the other hand, in some atoms the nucleus holds two or more extra—or valency—electrons. When such atoms meet, there is quite a lot of jumping over and binding to do, as a result of which quite complex molecules, often consisting of thousands of atoms, are formed. There are also the so-called 'homopolar' molecules, that is molecules made up of two identical atoms, but that is a very unpleasant situation."

"Unpleasant, why?" asked Mr Tompkins, getting interested again.

"Too much work," commented the electron, "to keep them together. Some time ago I happened to get that job and I didn't have a moment to myself all the while I stayed there. Why, it isn't at all the way it is here where the valency electron just enjoys himself and lets the electrically hungry and deserted atom stand by. No sir! In order to keep the two identical atoms together, he has to jump to and fro, from one to the other and back again. My word! One feels like a ping pong ball."

Mr Tompkins was rather surprised to hear the electron, which did not know what scrambled eggs were, speak so glibly of ping pong, but he let it pass.

"I'll never take on that job again!" grumbled the lazy electron, overwhelmed by a wave of unpleasant memories. "I am quite comfortable where I am now."

"Wait!" he exclaimed suddenly. "I think I see a still better place for me to go. So lo-o-o-ong!" And with a giant leap he rushed toward the interior of the atom.

Looking in the direction in which his interlocutor had gone, Mr

Tompkins understood what had happened. It seems that one of the electrons of the inner circle was thrown clear of the atom by some foreign high-speed electron which had unexpectedly penetrated into their system, and a cozy place in the "K" shell was now wide open. Chiding himself for missing this opportunity to join the inner circle, Mr Tompkins now watched with great interest the course of the electron he had just been talking to. Deeper and deeper into the atomic interior this happy electron sped, and bright rays of light accompanied his triumphant flight. Only when it finally reached the internal orbit did this almost unbearable radiation finally stop.

"What was that?" asked Mr Tompkins, his eyes aching from the sight of this unexpected phenomenon. "Why all this brilliance?"

"Oh that's just the X-ray emission connected with the transition," explained his orbit companion, smiling at his embarrassment. "Whenever one of us succeeds in getting deeper into the interior of the atom, the surplus energy must be emitted in the form of radiation. This lucky fellow made quite a big jump and let loose a lot of energy. More often we have to be satisfied with smaller jumps, here in the atomic suburbs, and then our radiation is called 'visible light'—at least that is what Father Paulini calls it."

"But this X-light, or whatever you call it, is also visible," protested Mr Tompkins. "I should call your terminology rather misleading."

"Well, we are electrons and are susceptible to any kind of radiation. But Father Paulini tells us that there exist gigantic creatures, 'Human Beings' he calls them, who can see light only when it falls within a narrow energy-interval, or wavelength-interval as he puts it. He told us once that it took a great man, Roentgen I think his name was, to discover these X-rays and that now they are largely used in something called 'medicine'."

"Oh yes. I know quite a lot about that," said Mr Tompkins, feeling proud that now *he* could show off his knowledge, "Want me to tell you more about it?"

"No thanks," said the electron yawning. "I really don't care. Can't you be happy without talking? Try to catch me!"

For a long time Mr Tompkins went on enjoying the pleasant sensation of diving through space with the other electrons in a kind of glorified trapeze act. Then, all of a sudden he felt his hair stand on end, an experience he had felt once before during a thunder storm in the mountains. It was clear that a strong electric disturbance was approaching their atom, breaking the harmony of the electronic motion, and forcing the electrons to deviate seriously from their normal tracks. From the point of view of a human physicist, it was only a wave of ultraviolet light passing through the spot where this particular atom happened to be, but to the tiny electrons it was a terrific electric storm.

"Hold on tight!" yelled one of his companions, "or you will be thrown out by photo-effect forces!" But it was already too late. Mr Tompkins was snatched away from his companions and hurled into space at a terrifying speed, as neatly as if he had been seized by a pair of powerful fingers. Breathlessly he hurtled further and further through space, tearing past all kinds of different atoms so fast he could hardly distinguish the separate electrons. Suddenly a large atom loomed up right in front of him and he knew that a collision was unavoidable.

"Pardon me, but I am photo-effected and cannot . . ." began Mr Tompkins politely, but the rest of the sentence was lost in an ear-splitting crash as he ran head on into one of the outer electrons. The two of them tumbled head over heels off into space. However, Mr Tompkins had lost most of his speed in the collision and was now able to study his new surroundings somewhat more closely. The atoms

which towered around him were much larger than any he had seen before, and he could count as many as twenty-nine electrons in each of them. If he had known his physics better he would have recognized them as atoms of copper, but at these close quarters the group as a whole did not look like copper at all. Also they were spaced rather close to one another forming a regular pattern which extended as far as he could see. But what surprised Mr Tompkins most was the fact that these atoms did not seem to be very particular about holding on to their quota of electrons, particularly their outer electrons. In fact the outer orbits were mostly empty, and crowds of unattached electrons were drifting lazily through space, stopping from time to time but never for very long, on the outskirts of one atom or another. Rather tired after his breakneck flight through space, Mr Tompkins tried at first to get a little rest on a steady orbit of one of the copper atoms. However he was soon infected with the prevailing vagabondish feeling of the crowd, and he joined the rest of the electrons in their nowhere-in-particular motion.

"Things are not very well organized here," he commented to himself, "and there are too many electrons not tending to their business. I think Father Paulini should do something about it."

"Why should I?" said the familiar voice of the monk who had suddenly materialized from nowhere. "These electrons are not disobeying my commandments, and besides they are doing a very useful job indeed. You may be interested to know that if all atoms cared as much about holding their electrons as some of them do, there would be no such thing as electric conductivity. Why you wouldn't even be able to have an electric bell in your house, to say nothing of a light or a telephone."

"Oh, you mean these electrons carry electric current?" asked Mr Tompkins, grasping at the hope that the conversation was turning to

a subject more or less familiar to him. "But I don't see that they are moving in any particular direction."

"First of all, my lad," said the monk severely, "do not use the word 'they', use 'we'. You seem to forget that you are an electron yourself and that the moment someone presses the button to which this copper wire is attached, electric tension will cause you, as well as all the other conductivity electrons, to rush along to call the maid or do whatever else is needed."

"But I don't want to!" said Mr Tompkins firmly, a note of temper in his voice. "As a matter of fact I am quite tired of being an electron and I don't think it's so much fun any more. What a life, to have to carry out all these electronic duties for ever and ever!"

"Not necessarily forever," countered Father Paulini, who definitely did not like back-talk on the part of plain electrons. "There is always the chance that you will be annihilated and cease to exist."

"B-b-be annihilated?" repeated Mr Tompkins feeling cold shivers running up and down his spine. "But I always thought electrons were eternal."

"That is what physicists used to believe until comparatively recent times," agreed Father Paulini, amused at the effect produced by his words, "but it isn't exactly correct. Electrons can be born, and die, as well as human beings. There isn't, of course, such a thing as dying of old age; death comes only through collisions."

"Well, I had a collision only a short while ago, and a pretty bad one too," said Mr Tompkins recovering a little confidence. "And if that one didn't put me out of action, I can't imagine one that would."

"It isn't a question of how forcibly you collide," Father Paulini corrected him, "but of who the other fellow is. In your recent collision you probably ran into another negative electron, very similar to your-

self, and there is not the slightest danger in such an encounter. In fact, you could butt into each other like a couple of rams for years and no harm could be done. But there is another breed of electron, the positive ones, which have been discovered only comparatively recently by the physicists. These positive electrons, or positrons, look exactly the way you do, the only difference being that their electric charge is positive instead of negative. When you see such a fellow approaching, you think it is just another innocent member of your tribe and go ahead to greet him. But then you suddenly find that, instead of pushing you away slightly to avoid a collision, as any normal electron would, he pulls you right in. And then it is too late to do anything."

"How terrible!" exclaimed Mr Tompkins. "And how many poor ordinary electrons can one positron eat up?"

"Fortunately only one, since in destroying a negative electron the positron also destroys itself. One could describe them as members of a suicide club, looking for partners in mutual annihilation. They do not harm one another, but as soon as a negative electron comes their way, it hasn't much chance of surviving."

"Lucky I haven't run into one of these monsters yet," said Mr Tompkins much impressed by this description. "I hope they are not very numerous. Are they?"

"No, they're not. And for the simple reason that they are always looking for trouble and so vanish very soon after they are born. If you wait a minute, I shall probably be able to show you one."

"Yes, here we are," continued Father Paulini after a short silence. "If you look carefully at that heavy nucleus over there, you will see one of these positrons being born."

The atom at which the monk was pointing was evidently undergoing a strong electromagnetic disturbance owing to some vigorous radiation

falling on it from outside. It was a much more violent disturbance than the one which threw Mr Tompkins out of his chlorine atom, and, the family of atomic electrons surrounding the nucleus was being dispersed and blown away like dry leaves in a hurricane.

"Look closely at the nucleus," said Father Paulini, and concentrating his attention Mr Tompkins saw a most unusual phenomenon taking place in the depths of the destroyed atom. Very close to the nucleus, inside the inner electronic shell, two vague shadows were gradually taking shape, and a second later Mr Tompkins saw two glittering brand new electrons rushing at great speed away from their birthplace.

"But I see two of them," said Mr Tompkins, fascinated by the sight.

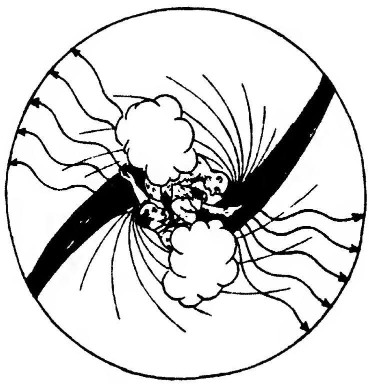
"That is right," agreed Father Paulini. "Electrons are always born in pairs, otherwise it would contradict the law of conservation of electric charge. One of these two particles, born under the action of a strong gamma ray on the nucleus, is an ordinary negative electron, whereas the other is a positron—the murderer. He is off now to find a victim."

"Well, if the birth of each positron destined to destroy an electron is accompanied by the birth of still another plain electron, then things aren't so bad," commented Mr Tompkins thoughtfully. "At least it doesn't lead to the extinction of the electronic tribe, and I . . ."

"Look out!" interrupted the monk shoving him aside while the newborn positron whistled by, just an inch away. "You can never be too careful when these murderous particles are around. But I think I'm spending too much time talking to you and I have other business to attend to. I must look for my pet 'neutrino' . . ." And the monk disappeared without letting Mr Tompkins know what this "neutrino" was and whether or not it was also to be feared. Thus deserted, Mr Tompkins felt even more lonely than before, and when one or another fellow

electron approached him on his journey through space, he even nursed a secret desperate hope that under each innocent exterior might be hidden the heart of a murderer. For a long time, centuries it seemed to him, his fears and hopes were not justified, and he unwillingly bore the dull duties of a conductivity electron.

Then suddenly it happened, and at a moment when he expected it



least. Feeling a strong need to talk to somebody, even to a stupid conductivity electron, he approached a particle which was slowly moving by and was evidently a newcomer to this bit of copper wire. Even at a distance, however, he noticed that he had made a bad choice and that an irresistible force of attraction was pulling him along, permitting no retreat. For a second he tried to struggle and tear himself away, but the distance between them was rapidly getting smaller and smaller and it seemed to Mr Tompkins that he saw a fiendish grin on the face of his captor.

"Let me go! Let me go!" shouted Mr Tompkins at the top of his

voice, struggling with his arms and kicking his legs. "I don't want to be annihilated; I'll conduct electric current for the rest of eternity!". But it was all in vain, and the surrounding space was suddenly illuminated by a blinding flash of intensive radiation.

"Well, I am no more," thought Mr Tompkins, "but how is it I can still think? Has my body only been annihilated, and my soul gone to a quantum heaven?" Then he felt a new force, more gentle this time, shaking him firmly and resolutely, and opening his eyes he recognized the university janitor.

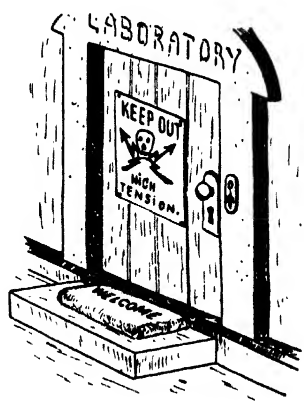
"I'm sorry, Sir," he said, "but the lecture was over some time ago and we gotta close the hall up now." Mr Tompkins stifled a yawn and looked sheepish.

"Good night, Sir," said the janitor with a sympathetic smile.

Third Dream

THE WOODCARVER

IT WAS a large and heavy door with an impressive sign, KEEP OUT —HIGH TENSION, right in the middle of it. However, this first inhospitable impression was somewhat softened by the word "welcome" written large on the door mat, and, after a minute's hesitation, Mr Tompkins pressed the door bell.



Let in by a young assistant, Mr Tompkins found himself in a large room a good half of which was occupied by a very complicated and fantastic looking machine.

"This is our large cyclotron or 'atom-smasher', as they call it in the newspapers," explained the assistant putting a loving hand on one of the coils of the giant electromagnet which represented the main part of this impressive looking tool of modern physics.

"It produces particles with energy up to ten million electron volts," he added proudly, "and there are not many nuclei which can withstand an impact of a projectile moving with such terrific energy!"

"Well," said Mr Tompkins, "these nuclei must be pretty tough! Imagine having to build a giant thing like that just to crack the tiny nucleus of a tiny atom. How does this machine work anyway?"

"This is our large cyclotron or 'atom-smasher'"

"Have you ever been to the circus?" asked his father-in-law emerging from behind the giant frame of the cyclotron.

"Err . . . yes, of course," said Mr Tompkins, rather embarrassed by this unexpected question, "you mean you want me to go to the circus with you tonight?"

"Not exactly," smiled the professor, "but that will help you to understand how a cyclotron works. If you look between the poles of this large magnet, you will notice a circular copper box which serves as a circus ring on which various charged particles, used in experiments on nuclear bombardment, are being accelerated. In the center of this box is located the source from which these charged particles, or ions, are produced. When they come out, they possess very small velocities, and the strong field of the magnet bends their trajectories into tiny circles around the center. Then we begin to whip them up to higher and higher velocities."

"I see how you can whip a horse," said Mr Tompkins, "but how you do the same thing with these tiny particles is rather above my head."

"Nevertheless, it is very simple. If the particle is moving in a circle, all one has to do is to apply to it a series of successive electric shocks each time it passes a given point on its trajectory, just as a trainer in the circus stands on the edge of the ring and whips the horse each time it passes by."

"But the trainer can see the horse," protested Mr Tompkins. "Can *you* see a particle rotating in this copper box to give it a kick just at the proper moment?"

"Of course I can't," agreed the professor, "but it isn't necessary. The whole trick of this cyclotron arrangement is that, although the accelerated particle always moves faster and faster, it always executes one complete turn in the same period of time. The point is, you see, that with

the increasing velocity of the particle, the radius, and consequently the total length, of its circular trajectory also increases proportionately. Thus it moves along an unwinding spiral, and always comes to the same side of the 'ring' at regular intervals. All one has to do is to place there some electric device to give the shocks at regular intervals, and we do it by means of an oscillating electric circuit system, which is very similar to those you can see at any broadcasting station. Each electric shock produced here is not very strong, but their cumulative effect speeds up the particle to extremely high velocities. This is the great advantage of this apparatus; it gives an effect equivalent to that of many million volts, although nowhere in the system are such high tensions actually present."

"Very ingenious indeed," said Mr Tompkins thoughtfully. "Whose invention is it?"

"It was first built by E. O. LAWRENCE at the University of California a few years ago," answered the professor. "Since then cyclotrons have been growing in size and spreading through physical laboratories with the speed of rumor. They seem to be really more convenient than the older devices which used cascade transformers, or machines based on the electrostatic principle."

"But can't one really break the nucleus without all these complicated devices?" asked Mr Tompkins, who was a great believer in simplicity, and didn't quite trust anything more complicated than a hammer.

"Of course one can. In fact when Rutherford made his first famous experiments on the artificial transformation of elements, he just used ordinary alpha particles emitted by naturally radio-active bodies. But that was over twenty years ago and, as you can see, the techniques of atom smashing have made considerable progress since then."

"Can you show me an atom actually being smashed?" asked Mr

Tompkins, who always preferred to see things for himself rather than to listen to lengthy explanations.

"Gladly," said the professor. "We were just starting an experiment. Here we are making a further study of the disintegration of boron under the impact of fast protons. When the nucleus of a boron atom is hit by a proton hard enough to permit the projectile to pierce the nuclear potential barrier and get inside, it breaks into three equal fragments which all fly in different directions. This process can be directly observed by means of the so-called 'cloud chamber' which enables us to see the trajectories of all the particles involved in the collision. Such a chamber, with a piece of boron in the middle, is now attached to the opening of the acceleration chamber, and as soon as we start the cyclotron working you will see the process of nuclear cracking with your own eyes."

"Will you please switch on the current," he said, turning to his assistant, "while I try to tune up the magnetic field."

It took some time to get the cyclotron started, and left alone Mr Tompkins wandered idly around the lab. His attention was drawn to a complicated system of large amplifier tubes glowing with a faint bluish light. Being quite unaware of the fact that the generating electric tensions used in the cyclotron, though not high enough to crack a nucleus, can easily floor an ox, he leaned forward to look at them more closely.

There was a sharp crack, like that of a lion tamer's whip, and Mr Tompkins felt a terrible shock running through his entire body. The next moment everything went black and he lost consciousness.

* * * * *

When he opened his eyes, he found himself prostrate on the floor where the electric discharge had thrown him. The room around him seemed the same, but all the objects in it had changed considerably.

Instead of the towering cyclotron magnet, shining copper connections, and dozens of complicated electric gadgets attached to every possible spot, Mr Tompkins saw a long wooden work table covered with simple carpenter's tools. On the old-fashioned shelves attached to the wall, he noticed a large number of different wood carvings of strange and unusual shapes. An old, friendly-looking man was working at the table, and looking more closely at his features, Mr Tompkins was struck by his strong resemblance both to the old man Gepetto in Walt Disney's Pinocchio, and the portrait of the late Lord Rutherford of Nelson hanging on the wall of the professor's lab.

"Excuse my intrusion," said Mr Tompkins, raising himself from the floor, "but I was visiting a nuclear laboratory, and something strange seems to have happened to me."

"Oh, you are interested in nuclei," said the old man, setting aside the piece of wood he was carving. "Then you came to just the right place. I make all kinds of nuclei right here and will be glad to show you around my little workshop."

"You say you *make* them?" said Mr Tompkins rather stupefied.

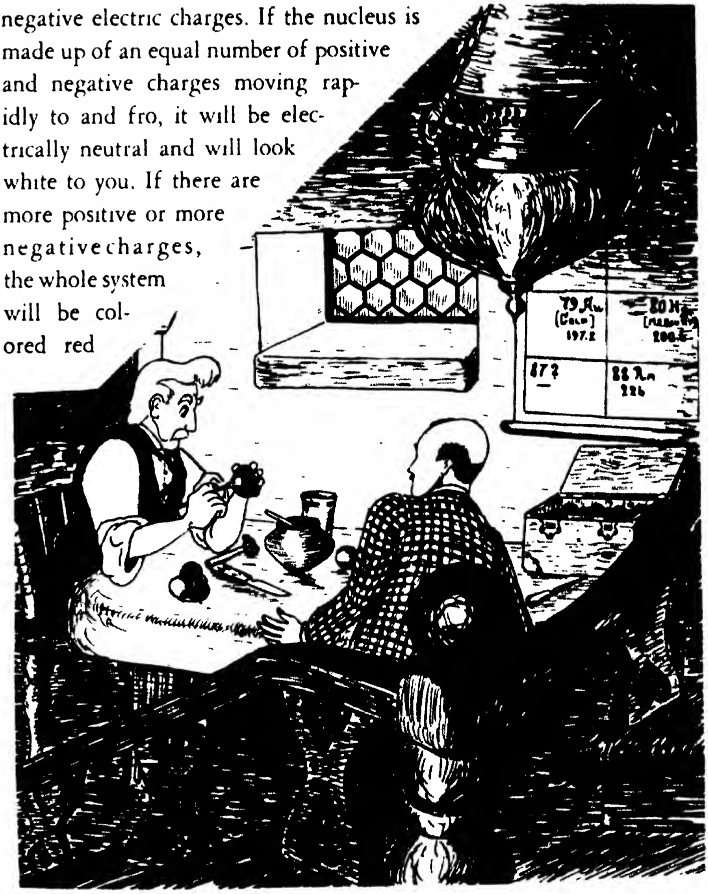
"Yes, of course. Naturally, it requires some skill, especially in the case of radioactive nuclei, which may fall apart before you even have time to paint them."

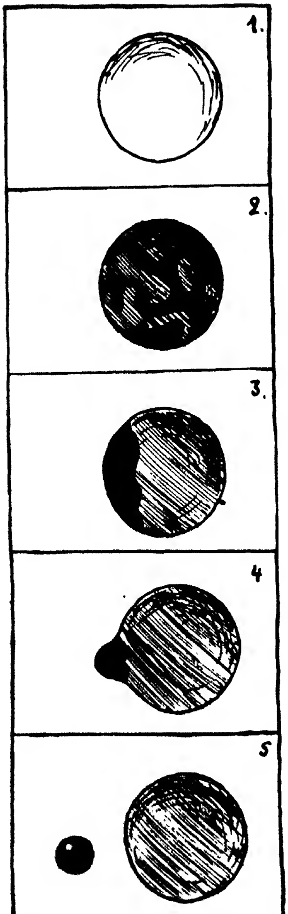
"*Paint* them?"

"Yes. I use red for the positively charged particles and green for the negative ones. Now you probably know that red and green are what one calls 'complementary colors', and cancel each other out if mixed together.[1] This corresponds to the mutual cancellation of positive and

[1] The reader must keep in mind that the mixture of colors pertains only to light rays and not to the paints themselves. If we mix red and green paint we shall simply get a dirty color. On the other hand if we paint one half of a toy top red, and the other green, and then spin it rapidly, it will look white.

negative electric charges. If the nucleus is made up of an equal number of positive and negative charges moving rapidly to and fro, it will be electrically neutral and will look white to you. If there are more positive or more negative charges, the whole system will be colored red





or green. Simple, isn't it?"

"Now," continued the old man, showing Mr Tompkins two large wooden boxes standing near the table, "this is where I keep the materials from which various nuclei can be built. The first box contains *protons*, these red balls here. The are quite stable and keep their color permanently, unless you scratch it off with a knife or something. I have much more trouble with the so-called *neutrons* in the second box. They are normally white, or electrically neutral, but show a strong tendency to turn into red protons. As long as the box is closed tight, everything is all right, but as soon as you take one out, see what happens."

Opening the box, the old woodcarver took out one of the white balls and placed it on the table. For a while nothing seemed to happen, but just when Mr Tompkins had about lost patience, the ball suddenly came alive. Irregular reddish and greenish stripes appeared on its surface, and for a short while the ball looked like one of the colored glass marbles children like so much. Then the green color became concentrated

on one side, and finally separated itself entirely from the ball, forming a brilliant green droplet which fell on to the floor. The ball itself was now left completely red, no different from any of the red-colored protons in the first box.

"You see what happens," he said, picking the drop of green paint, now quite hard and round, up from the floor. "The white color of the neutron broke up into red and green and the whole thing split into two separate particles, a proton and a negative electron."

"Yes," he added, seeing the surprised look on Mr Tompkins' face, "This jade-colored particle is nothing but an ordinary electron, just like any other electron in any atom or anywhere else.

"Gosh!" exclaimed Mr Tompkins, "This certainly tops any colored handkerchief trick I have ever seen. But can you change the colors back again?"

"Yes, I can rub the green paint back on to the surface of the red ball and make it white again, but that would require some energy, of course. Another way to do it would be to scratch the red paint off, which would take some energy too. Then the paint scratched from the surface of the proton will form a red droplet, that is, a positive electron, about which you have probably heard."

"Yes, when I was an electron myself . . ." began Mr Tompkins, but checked himself quickly. "I mean, I have heard that positive and negative electrons annihilate each other whenever they meet," he said. "Can you do that trick for me too?"

"Oh, it's very simple," said the old man. "But I won't take the trouble to scratch the paint off this proton, as I have a couple of positrons left over from my morning's work."

Opening one of the drawers, he extracted a tiny bright red ball, and, pressing it firmly between finger and thumb, put it beside the green one

on the table. There was a sharp noise, like a fire-cracker exploding, and both balls vanished at once.

"You see?" said the woodcarver, blowing on his slightly burned fingers, "That is why one cannot use electrons for building nuclei. I tried it once, but gave it up right away. Now I use only protons and neutrons."

"But neutrons are unstable too, aren't they?" asked Mr Tompkins, remembering the recent demonstration.

"When they are alone, yes. But when they are packed tightly in the nucleus, and surrounded by other particles, they become quite stable. However, if there are, relatively speaking, too many neutrons, or too many protons, they can transform themselves, and the extra paint is emitted from the nucleus in the form of negative or positive electrons. Such an adjustment we call a beta-transformation."

"Do you use any glue, in making the nuclei?" asked Mr Tompkins with interest.

"Don't need any," answered the old man, "These particles, you see, stick to each other by themselves as soon as you bring them into contact. You can try it yourself if you want to."

Following this advice, Mr Tompkins took one proton and one neutron in each hand, and brought them together carefully. At once he felt a strong pull, and looking at the particles he noticed an extremely strange phenomenon. The particles were exchanging color, becoming alternately red and white. It seemed as if the red paint were 'jumping' from the ball in his right hand to the one in his left hand, and back again. This twinkling of color was so fast that the two balls seemed to be connected by a pinkish band along which the coloring was oscillating to and fro.

"This is what my theoretical friends call the exchange phenomenon,"

said the old master, chuckling at Mr Tompkins' surprise. "Both balls want to be red, or to have the electric charge, if you want to put it that way, and as they cannot have it simultaneously, they pull it to and fro alternately. Neither wants to give up, and so they stick together until you separate them by force. Now I can show you how simple it is to make any nucleus you want to. What shall it be?"

"Gold," said Mr Tompkins, remembering the ambition of the medieval alchemists.

"Gold?" Let us see," murmured the old master, turning to a large chart hanging on the wall, "The nucleus of gold weighs one hundred and ninety-seven units, and carries seventy-nine positive electric charges. That means I have to take seventy-nine protons and add one hundred and eighteen neutrons to get the mass correct."

Counting off the proper number of particles, he put them into a tall cylindrical vessel and covered it all with a heavy wooden piston. Then, with all his strength, he pushed the piston down.

"I must do this," he explained to Mr Tompkins, "because of the strong electric repulsion between the positively charged protons. Once this repulsion is overcome by the pressure of the piston, the protons and the neutrons will stick together because of their mutual exchange forces, and will form the desired nucleus."

Pressing the piston in as far as it would go, he took it out again and quickly turned the cylindrical vessel upside down. A glittering pinkish ball rolled out on the table, and, watching it more closely, Mr Tompkins noticed that the pinkish color was due to an interplay of red and white flashes among the rapidly moving particles.

"How beautiful!" he exclaimed, "So this is an atom of gold!"

"Not an atom yet, only the atomic nucleus," the old woodcarver corrected him. "To complete the atom you must add the proper number

of electrons to neutralise the positive charge of the nucleus, and make the customary electronic shell around it. But that is easy, and the nucleus itself will catch its electrons as soon as there are some around."

"Funny," said Mr Tompkins, "that my father-in-law never mentioned that one could make gold so simply."

"Oh your father-in-law and those other so-called nuclear physicists!" exclaimed the old man with a touch of irritation in his voice. "They put on a fine show but they can actually do very little. They say they cannot compress separate protons into a complex nucleus because they cannot exert great enough pressure to do the job. One of them even calculated that one would need to impose the entire weight of the moon to make the protons stick together. Well, why don't they get the moon if that is their only trouble?"

"But still they produce *some* nuclear transformation," remarked Mr Tompkins meekly.

"Yes, of course, but awkwardly and to a very limited extent. The quantity of the new elements they get is so small they can hardly see it themselves. I will show you how they do it." And, taking a proton, he threw it with considerable force against the gold nucleus lying on the table. Nearing the outside of the nucleus, the proton slowed down a little, hesitated a moment and then plunged inside it. Having swallowed the proton, the nucleus shivered for a short time as though in a high fever and then a small part of it broke off with a crack.

"You see," he said, picking up the fragment, "this is what they call an alpha particle, and if you inspect it closely you will notice that it consists of two protons and two neutrons. Such particles are usually ejected from the heavy nuclei of the so-called radioactive elements, but one can also kick them out of ordinary stable nuclei if one hits them hard enough. I must also call your attention to the fact that the larger

fragment left on the table is not a gold nucleus any longer; it has lost one positive charge and is now a nucleus of platinum, the preceding element in the periodic table. In some cases, however, the proton which enters the nucleus will not cause it to split in two parts, and as the result you will get the nucleus that follows gold in the table, i.e. the nucleus of mercury. Combining these and similar processes one can actually transform any given element into any other."

"Oh now I see why they use fast proton beams produced by the cyclotron," said Mr Tompkins, beginning to understand. "But why do you say this method is no good?"

"Because its effectiveness is extremely low. First of all they cannot aim their projectiles the way I can so that only one in several thousand shots actually hits the nucleus. Second, even in the case of a direct hit, the projectile is very likely to bounce off the nucleus instead of penetrating into the interior. You may have noticed when I threw the proton into the gold nucleus that it hesitated somewhat before going in, and I thought for a moment that it was going to be thrown back."

"What is there to prevent the projectiles from going in?" asked Mr Tompkins with interest.

"You could have guessed it yourself," said the old man, "if you had remembered that both the nuclei and the bombarding protons carry positive charges. The repulsive force between these charges forms a kind of barrier which is not so easy to cross. If the bombarding protons manage to penetrate the nuclear fortress, it is only because they use something like the Trojan horse technique; they go through the nuclear walls not as particles but as waves."

"Well, you have got me there," said Mr Tompkins sadly, "I don't understand a word you are saying."

"I was afraid you wouldn't," said the woodcarver with a smile. "To

tell you the truth, I'm a workman myself. I can do these things with my hands but I'm not too strong on this theoretical abracadabra either. However the main point is that, as all these nuclear particles are made out of quantum material, they can always go, or rather leak, through obstacles ordinarily considered impenetrable."

"Oh, I see what you mean!" exclaimed Mr Tompkins. "I remember that once, shortly before I met Maud, I visited a strange place where billiard balls behaved exactly the way you describe.[2]

"Billiard balls? You mean real *ivory* billiard balls?" repeated the old woodcarver eagerly.

"Yes, I understand they were made from the tusks of quantum elephants," answered Mr Tompkins.

"Well, such is life," said the old man sadly. "They use such expensive materials just for games, and I have to carve protons and neutrons, the basic particles of the entire universe, out of plain quantum oak!"

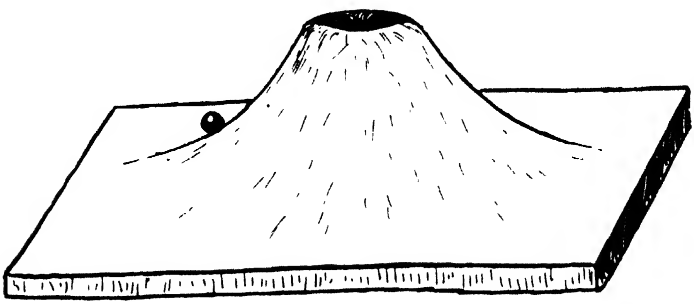
"But," he continued, trying to hide his disappointment, "my poor wooden toys are just as good as all those expensive ivory creations and I will show you how neatly they can pass through any kind of barrier." And, climbing on the bench, he took from the top shelf a very strange carved figure looking like the model of a volcano.

"What you see here," he continued, gently brushing off the dust, "is the model of the barrier of repulsive forces surrounding any atomic nucleus. The outer slopes correspond to the electric repulsion between the charges, and the crater to the cohesion forces which make the nuclear particles stick together. If I now flip a ball up the slope, but not hard enough to bring it over the crest, you would naturally suppose that it would roll back again. But see what actually happens . . ." and he gave the ball a slight flip.

[2] This was Mr Tompkins' dream in the Quantum Room. See *Mr Tompkins in Wonderland*, Cambridge University Press and The Macmillan Co., 1940.

"Well, I don't see anything unusual," said Mr Tompkins, when the ball, after rising about half way up the slope, rolled back again on the table.

"Wait," said the woodcarver quietly. "You shouldn't expect it at the first trial," and he sent the ball up the slope once more. This time it failed again, but at the third attempt the ball suddenly disappeared



just when it was about half way up the slope.

"Well, where do you suppose that one went?" said the old woodcarver triumphantly with the air of a magician.

"You mean it is in the crater now?" asked Mr Tompkins.

"Yes, that is exactly where it is," said the old man, picking out the ball with his fingers.

"Now, let us get it in reverse," he suggested, "and see if the ball can get out of the crater without rolling over the top," and he threw the ball back into the hole.

For a while nothing happened, and Mr Tompkins could hear only the slight rumbling of the ball rolling to and fro in the crater. Then,

as by a miracle, the ball suddenly appeared in the middle of the outer slope, and quietly rolled down to the table.

"What you see here is a very good representation of what happens in radioactive alpha-decay," said the woodcarver, putting the model back into its place, "only there, instead of the ordinary quantum-oak barrier, you have the barrier of repulsive electric force. But in principle there is no difference whatever. Sometimes these electric barriers are so 'transparent' that the particle escapes in a small fraction of a second; sometimes they are so 'opaque' that it takes many billion years, as for example in the case of the Uranium nucleus."

"But why aren't all nuclei radioactive?" asked Mr Tompkins.

"Because in most nuclei the floor of the crater is below the outer level, and only in the heaviest known nuclei is the floor sufficiently elevated to make such an escape possible."

It is difficult to say how many hours Mr Tompkins spent in the workshop with the kindly old woodcarver, who was always so eager to communicate his knowledge to anyone who came along. He saw many other unusual things, and above all a carefully closed, but apparently empty casket labelled: NEUTRINOS. *Handle with care and don't let out.*

"Is there something in it?" asked Mr Tompkins, shaking the casket near his ear.

"I don't know," said the woodcarver. "Some people say yes, some say no. But you can't see anything anyway. That's a fancy casket given to me by one of my theoretical friends, and I don't quite know what to do with it. Better leave it alone for the time being."

Continuing his inspection, Mr Tompkins also discovered a dusty old violin, which looked so old that it must have been made by Stradivari's grandfather.

"Do you play the violin?" He turned to the woodcarver.

"Only gamma-ray tunes," answered the old man. "It is a quantum-violin, and it doesn't play anything else. Once I had a quantum-cello, for optical tunes, but somebody borrowed it and never brought it back."

"Well, play me a gamma-ray tune," asked Mr Tompkins. "Never heard one before."

"I will play you *'Nucleét in Th C Sharp',*" said the woodcarver,

raising the violin to his shoulder, "but you must be prepared for it to be a very sad tune."

The music was very strange indeed, unlike anything Mr Tompkins had ever heard before. There was a steady noise of ocean waves running on sandy shores, interrupted from time to time by a shrill tune reminding him of the whistle of a passing bullet. Mr Tompkins was not exactly musical, but this tune had a weird and powerful effect on him. He stretched himself comfortably in an old armchair and closed his eyes . . .

* * * * *

"I am sure he will live now," he heard a hushed voice at his side. "It's lucky that the current didn't pass directly through the brain."

"Oh, thank you, Doctor! I had almost lost hope," said another voice, which he recognized as his wife's.

Slowly Mr Tompkins opened his eyes. He was resting on a comfortable white bed, and Maud was sitting on the edge of it.

"Oh, darling!" she exclaimed, bending over him, "I'm so glad you are getting better. But you must promise me right away never, never to go to one of those terrible atom smashing places again."

"I promise," said Mr Tompkins, taking her hand.

"And that you won't talk to father about physics any more. It seems to have a bad effect on your nerves."

"I promise that too," breathed Mr Tompkins, and his whispering voice showed sincerity and satisfaction.

Appendix

FOUR LECTURES

BY THE PROFESSOR

(which inspired
Mr Tompkins' dreams)

First Lecture [1]

THE REALITY OF ATOMS

Ladies and Gentlemen:

You have all heard, of course, about *atoms* and *molecules,* those tiny particles which form the structure of all material bodies. I am afraid, however, that many of you are still inclined to consider the existence of these fundamental constituent parts of matter as somewhat hypothetical, unless you are able to "see them with your own eyes". I will make a point in this lecture, of trying to remove this probably natural distrust, and to show you that atoms and molecules are just as real as any other material object which you handle in everyday life.

One of the simplest ways to get an idea about the discontinuity of matter consists in experiments with thin layers of oil which spread over the surface of water. You have undoubtedly observed large rainbow colored patches of oil floating on the surface of harbor-waters, and many of you know from high-school physics that this coloring originates from the interference of light-rays reflected from the upper and lower surfaces of these oil-layers. The study of such thin oil-layers has shown however, that a given amount of oil can cover only a limited area, or that, in other words, there exists a lower limit for the thickness of such a layer. If one attempts to stretch such a thin layer over a still larger area, it will break up, and patches of free water surface will

[1] **Note by the Editor: This lecture was attended by Mr Tompkins together with his wife Maud, and gave most of the material for Maud's dream.**

appear here and there. It would be difficult to understand this result from the hypothesis of an absolute continuity of matter, since in that case there would be nothing to prevent one drop of oil from covering uniformly the entire surface of an ocean. If, however, you assume that matter consists of separate "grains", the minimum thickness will be that of a single layer of these "grains". We call such layers of minimum thickness, *"monomolecular layers"*, and their study can give us our first information about the real size of the molecules. In fact, it has been found that one cubic centimeter of oil can cover continuously an area of not more than several thousand square meters. It is easy to calculate from these data, that *the minimum thickness is several millionths of a millimeter,* and, according to the above *this must also represent the average diameter of a molecule.*

As you see, the experiment is very simple, does not require any complicated physical apparatus, and gives us definite information concerning the structure of matter. There is actually no reason why it could not have been performed by old DEMOCRITUS, who was the first to speak about the "grains of matter", and who could have thus given the proof of his views right then. Well, maybe I am not quite fair to the old philosopher; what seems easy for us now might not have been so twenty centuries ago.

The next important point concerning the internal structure of matter consists in the statement that the molecules are involved in a permanent irregular motion. We call it *"thermal motion"*, since we perceive this motion as the phenomenon of heat: the faster the motion, the hotter the body, the rising temperature being simply interpreted as the increase in the kinetic energy of separate molecules. All of you know, of course, that this "kinetic theory of heat" permits us to understand all the details of various heat-phenomena, such as, for example, the

change in the aggregate state of matter. In fact, at comparatively low temperatures the energy of thermal motion is low, and all molecules are cemented together by some kind of cohesive force, thus forming a solid body. As the temperature rises, the vibrations of the molecules forming a solid increase in intensity, and at a certain point (melting point) the molecules break loose from their fixed position and begin to slide freely along one another. Thus we get a liquid which does not keep its shape. At a still higher temperature (boiling point) separate molecules become entirely disengaged and fly freely through space, forming a gas with its tendency to unlimited expansion.

Since the transition from the solid state into liquid, and from the liquid into gas, is the result of a conflict between the thermal motion of molecules and the cohesive forces between them, the values of melting- and boiling-points vary a great deal from substance to substance. Thus, for example, for iron, where the cohesive forces are rather strong, a very high temperature is needed to break up the solid or to disengage molecules entirely from one another. On the other hand, the molecules of oxygen, nitrogen, and other common gases possess such weak cohesive forces, that they can exist as liquids or solids only at extremely low temperatures. It may be added here that the interpretation of temperature as the intensity of thermal motion of molecules leads naturally to the notion of the lowest possible—or the *"absolute zero"*—temperature, as the temperature at which all molecular motion entirely stops. This "absolute zero" lies, as you probably know, at —273 degrees Centigrade.

The best *direct* proof of the thermal motion of molecules is given by what is called the phenomenon of *Brownian* motion, which consists of a very fast irregular motion of tiny spores of various plants suspended in liquid. This strange behaviour of spores was first noticed by the

English botanist R. BROWN, and remained unexplained for a very long time, until at last, towards the end of the last century, it was interpreted as the direct result of the thermal motion of molecules. According to this interpretation Brownian particles represent, so to speak, an intermediate step between the familiar bodies of our everyday experience, and the microcosmos of atoms and molecules. They are still large enough to be observed through a good microscope, but, on the other hand, are just small enough to be pushed around by molecular collisions. Thus, looking on the tiny Brownian particles performing their eternal *danse macabre* in a drop of water, we are getting, as it were, an eyewitness' proof of the reality of molecules and their thermal motion. Studying in some detail the motion of these Brownian particles, which after all could be considered as some kind of oversized molecules, the French physicist JEAN PERRIN was able to confirm all the fundamental conclusions of the molecular theory of material structure, and the kinetic theory of heat, as decisively as if he had seen the molecules themselves with his own eyes.

But you may be still unsatisfied with the expression "as if with his own eyes", and would like to ask me to keep my promise to show you the molecules so that you could really see them without any "as ifs". All that I have to do to satisfy this legitimate desire, is to call for my first plate. (The plate please!)[2] Well, here we are. The picture which you see now on the screen, is not a modern wall-paper design as some of you may think, but a real photograph of atoms and molecules forming a crystal of chemical substance known as *Diopside.* It was taken some years ago by an English physicist W. L. BRAGG, and I am grateful to him for his permission to show it here.

You must not think, however, that photographing atoms is an easy

[2] *See frontispiece.*

job, and that all you have to do is to ask the subject to make a pleasant face and to press the button. In fact, taking photographs of such small objects as atoms and molecules, one has to take into account the fact that nothing will come out at all unless the wave length of illuminating light is smaller than the size of the object to be photographed; there is no way to paint a Persian miniature with a house-painting brush! Biologists, who work with tiny microorganisms, know this difficulty very well since the size of bacteria (about 0.0001 centimeters) is already comparable with the wave-length of visible light. In order to improve the sharpness of the image they take their microphotographs of bacteria in ultra-violet light, thus obtaining somewhat better results. But the size of molecules and their distance apart in a crystal lattice is, as I have mentioned before, so small that neither visible nor ultraviolet light will be any good. In order to see the molecules separately we must necessarily use radiation with a wave-length thousands of times shorter than that of visible light—or, in other words, we have to use the radiation called X-rays. But here we encounter a seemingly unsurmountable difficulty: it is known that X-rays pass through any substance *without showing any refraction phenomenon* so that it is quite impossible to build an X-ray lens, not to mention a microscope. This property of X-rays, together with their high penetrating power, is, of course, very useful in medical science, since the presence of refraction in the human body would completely destroy all X-ray photographs. But the same property seems to exclude any possibility of getting any enlarged picture by means of X-rays.

The situation looks at first sight pretty disappointing, but a good physicist can in most cases find a way around an obstacle, and Dr Bragg found in this case a very ingenious way indeed. He based his considerations on the mathematical theory of the microscope, developed by the

German optician Abbe, according to which any microscopic image may be considered as the overlapping of a large number of separate diffraction patterns. It is rather difficult to understand all the details of this theory without the complicated mathematical formulae, but you may get some idea about it by remembering the method of printing colored pictures by using a number of single-colored clichés. Looking at each separate color-print, you may not be able to tell what the picture actually represents but as soon as they all overlap in a proper way, the whole picture stands out clear and sharp. In a similar way, Bragg overlaps a number of separate diffraction patterns formed by the reflection of X-rays from the crystal in question, thus producing in the final count exactly the same effect as would be given by the nonexistent X-ray lens. Thus although the pictures made by Bragg's method are not actually obtained by a single click of the camera, and could jokingly be called "faked photographs", they are as good and correct as any real picture could be. In fact, you would not object to a photograph of a cathedral composed of several separate pictures, if for technical reasons one could not photograph the entire structure on one plate.

Now, I draw your attention again to the picture on the screen. As I have already said, it represents the structure of a *diopside crystal,* and by watching it carefully, you will not only see the regular pattern formed by diopside molecules in the crystal-lattice, but also the separate atoms forming each molecule. We know from chemistry that the diopside molecule is composed of one atom of Calcium, one atom of Magnesium, two of Silicon and six of Oxygen. Its chemical formula is in fact:

$$Ca\,Mg\,Si_2\,O_6$$

The darker spots running in a regular row across the photograph represent the shadows of Calcium and Magnesium atoms which overlap

owing to the particular angle at which the picture is taken. Lighter shadows correspond to Silicon and Oxygen atoms and you will have no difficulty in identifying them by using the schematic diagram given in the lower left corner. If you do not call that seeing atoms with your own eyes, I don't know what else would ever satisfy you!

Of course, the picture is somewhat diffuse; this is partly due to the fact that, unless you cool the crystal to absolute zero, its molecules vibrate around their positions of equilibrium, and the photographer cannot say to them, "Please be quiet." You can, as a matter of fact, get somewhat sharper pictures by plunging the crystal in liquid air; on the other hand, the photograph will get more and more diffuse and finally disappear when the temperature approaches the melting point. But, even if we take a photograph such as Bragg's at a temperature of absolute zero, all details of atomic structure will not show up, for quite a different reason. The point is that, in order to get a picture of inter-atomic structure, we should use a still shorter wavelength which will bring us from ordinary X-rays to the so-called gamma-rays emitted by radioactive substances. Now, you have probably heard that, according to the quantum theory, radiative energy is always collected into certain discrete portions, known as *"light-quanta"*, and that to enable us to see an object it is necessary for at least one light-quantum to be reflected from its surface. It is further known that the amount of energy concentrated in each such portion is inversely proportional to the wavelength of radiation. In particular, the energy of a "gamma-quantum" is so high that when it collides with an atomic electron it will throw it clear out of the atom. Thus the internal structure of atoms is, so to speak, too delicate to be seen, and we break the atom up before we are able to notice any features of its internal structure. We are faced here with a very peculiar situation concerning the observability of the tiny

atomic mechanisms. If we use light of comparatively long wavelength, the illumination will not do any harm to the atom (because light-quanta contain little energy), but the picture will be too diffuse to see any details. If on the other hand we use a very short wave-length which could show us all the minute details of atomic structure, the atom will be broken before we can see anything.

The situation which I have just described is very characteristic of modern developments of physics, and the principle behind the impossibility of telling as much as we would like about the structure of the atom, is known as the *"Uncertainty-principle"* of the quantum theory. You must not think, however, that this indeterminacy prevents us from understanding in full detail the laws of atomic structure, since all that it does is to force us to use a special language entirely different from that of classical physics. After all, it would be surprising if, coming to a world billions of times smaller than the world of our everyday experience, we were able to use the same language!

Those of you who have not been hopelessly bored by my exposition tonight and who will be brave enough to come again to my next lecture in this series, will be able to learn more about the way in which modern physics describes the internal structure of these tiny but highly complicated mechanisms—atoms.

Second Lecture[1]

INSIDE THE ATOM

Ladies and Gentlemen:

In my last lecture I promised to give you some more details concerning the internal structure of the atom, and to explain how the peculiar features of this structure account for its physical and chemical properties. You know, of course, that atoms are no longer considered as elementary indivisible constituent parts of matter, and that this role has passed now to much smaller particles such as electrons, protons, etc.

The idea of elementary constituent particles of matter, representing the last possible step in divisibility of material bodies, dates back to the ancient Greek philosopher DEMOCRITUS who lived in the fourth century B.C. Meditating about the hidden nature of things, Democritus came to the problem of the structure of matter and was faced with the question whether or not it can exist in infinitely small portions. Since it was not customary at this epoch to solve any problem by any other method than that of pure thinking, and since, in any case, the question was at that time beyond any possible attack by experimental methods, Democritus searched for the correct answer in the depths of his own mind. On the basis of some obscure philosophical considerations he finally came to the conclusion that it is "unthinkable" that matter could be divided into smaller and smaller parts without any limit, and that one must assume the existence of "the smallest particles which cannot be divided

[1] Note by the editor: This is the lecture during which Mr Tompkins fell asleep and had an unusual dream that he himself had become an atomic electron.

any more". He called such particles *"atoms"*, which, as you probably know, means "indivisibles" in Greek.

I do not want to minimize the great contribution of Democritus to the progress of natural science, but it is worth keeping in mind that besides Democritus and his followers, there was undoubtedly another school of Greek philosophy the adherents of which maintained that the process of divisibility of matter *could* be carried beyond any limit. Thus, independent of the character of the answer which had to be given in the future by exact science, the philosophy of ancient Greece was well secured with an honorable place in the history of physics. At the time of Democritus, and for centuries later, the existence of such indivisible portions of matter represented a purely philosophical hypothesis, and it was only in the nineteenth century that scientists decided that they had finally found these indivisible building-stones of matter which were foretold by the old Greek philosopher more than two thousand years ago.

In fact, in the year 1808, an English chemist JOHN DALTON showed that the relative proportions of various chemical elements which are needed to form more complicated chemical compounds can always be expressed by the ratio of integral numbers, and he interpreted this empirical law as due to the fact that all compound substances are built up from a varying number of particles representing simple chemical elements. The failure of medieval alchemy to turn one chemical element into another supplied a proof of apparent indivisibility of these particles, and without much hesitation they were christened by the old Greek name: *"atoms"*. Once given, the name stuck, and although we know now that these *"Dalton's atoms"* are not at all indivisible, and are, in fact, formed by a large number of still smaller particles, we close our eyes to the philological inconsistency of their name.

Thus the entities called "atoms" by modern physics are not at all the elementary and indivisible constituent units of matter imagined by Democritus, and the term "atom" would actually be more correct if it were applied to such much smaller particles as electrons and protons, from which "Dalton's atoms" are built. But such a change of names would cause too much confusion, and nobody in physics cares much about philological consistency anyway! Thus we retain the old name of *"atoms"* in Dalton's sense, and refer to electrons, protons, etc. as "elementary particles".

This name indicates, of course, that we believe at present that these smaller particles are *really* elementary and indivisible in Democritus' sense of the word, and you may ask me whether history will not repeat itself, and whether in the further progress of science, the elementary particles of modern physics will not be proved to be quite complex. My answer is that, although there is no absolute guarantee that this will not happen, there are very good reasons to believe that this time we are completely right. In fact, there are ninety-two different kinds of atoms (corresponding to ninety-two different chemical elements) and each kind of atom possesses rather complicated characteristic properties; a situation which in itself invites some simplification along the line of reducing such a complicated picture to a more elementary one. On the other hand, physics of today recognizes only a few different kinds of elementary particles: *electrons* (positive and negative light particles), *nucleons* (charged or neutral heavy particles, also known as *protons and neutrons*), and possibly the so-called *neutrinos* the nature of which has not been completely clarified.

The properties of these elementary particles are extremely simple, and very little simplification could be gained by further reduction; besides, as you will understand, you must always have several elementary

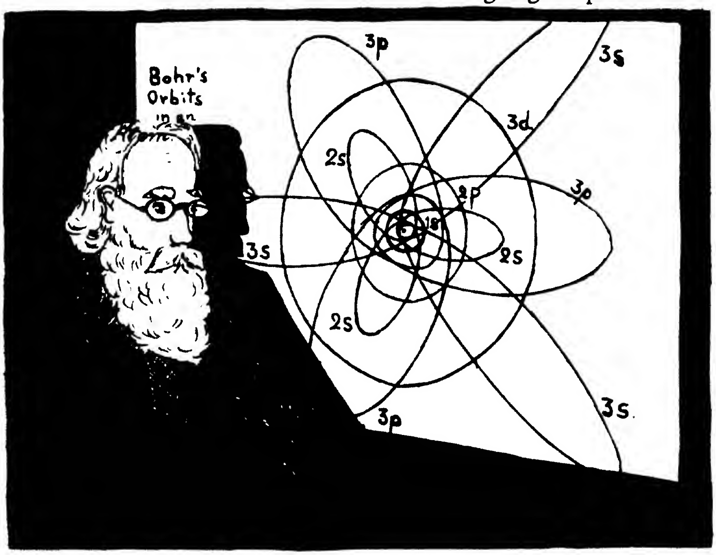
notions to play with if you want to build up something more complicated, and two or three elementary notions are not too many. Thus, in my opinion, it is quite safe to bet your last dollar that the elementary particles of modern physics will live up to their name.

Now we can turn to the question concerning the way in which Dalton's atoms are built up from the elementary particles. The first correct answer to this question was given in 1911 by the celebrated British physicist ERNEST RUTHERFORD (later Lord Rutherford of Nelson) who was studying atomic structure by bombarding various atoms with fast-moving minute projectiles, known as *alpha-particles,* which are emitted in the process of disintegration of radioactive elements. Observing the deflection (scattering) of these projectiles after passage through a piece of matter, Rutherford came to the conclusion that all atoms must possess a very dense positively charged central core (atomic nucleus) surrounded by a rather rarefied cloud of negative electric charge (atomic atmosphere). We know today that the atomic nucleus is made up of a certain number of *protons* and *neutrons,* known under the collective name of *"nucleons"*, held tightly together by strong cohesive forces, and that atomic atmosphere consists of varying numbers of negative electrons swarming around under the action of electrostatic attraction of the nuclear positive charge. The number of electrons forming the atomic atmosphere determines all the physical and chemical properties of a given atom, and varies along the natural sequence of chemical elements from one (for Hydrogen) up to ninety-two (for the heaviest known element: Uranium).

In spite of the apparent simplicity of Rutherford's atomic model, its detailed understanding turned out to be anything but simple. In fact, according to the best belief of classical physics, negatively charged electrons rotating around an atomic nucleus are bound to lose their energy

of motion through the process of radiation (light-emission), and it has been calculated that, owing to these steady energy losses, all electrons forming atomic atmosphere should collapse on the nucleus within a negligible fraction of a second. This seemingly sound conclusion of classical theory stands, however, in sharp contradiction with the empirical fact that atomic atmospheres are, on the contrary, quite stable, and that instead of collapsing on the nucleus, atomic electrons continue their swarming motion around the central body for an indefinite period of time. Thus we see that a very deep-rooted conflict arises between the basic ideas of classical mechanics, and the empirical data pertaining to the mechanical behavior of a tiny constituent part in the world of atoms. This fact brought the famous Danish physicist NIELS BOHR to the realisation that classical mechanics, which claimed for centuries a privileged and secure position in the system of natural sciences, should be from now on considered as a restricted theory, applicable to the macroscopic world of our everyday experience, but failing badly in its application to the much more delicate types of motion taking place within various atoms. As the tentative foundation for the new generalized mechanics which would be applicable also to the motion of the tiny moving parts of atomic mechanism, Bohr proposed to assume that *from all the infinite variety of types of motion considered in classical theory, only a few specially selected types can actually take place in nature.* These permitted types of motion, or trajectories, are to be selected according to certain mathematical conditions, known as the *quantum-conditions* of the Bohr theory. I am not going to enter here into a detailed discussion of these quantum-conditions, but will mention only that they have been chosen in such a way, that all the restrictions imposed by them become of no practical importance in all cases where the mass of the moving particles is much larger than the masses we

encounter in atomic structure. Thus, being applied to macroscopic bodies, the new *micro-mechanics* gives exactly the same results as the old classical theory (*principle of correspondence*) and it is only in the case of tiny atomic mechanisms that the disagreement between the two theories becomes of essential value. Without going deeper into the



details, I will satisfy your curiosity concerning the structure of the atom from the point of view of Bohr's theory, by showing the diagram of Bohr's quantum-orbits in an atom. (First plate, please!) You see here, on a largely magnified scale of course, the system of circular and elliptical orbits, which represent the only types of motion "permitted" for the electrons forming atomic atmosphere by Bohr's quantum conditions. Whereas classical mechanics would allow the electron to move

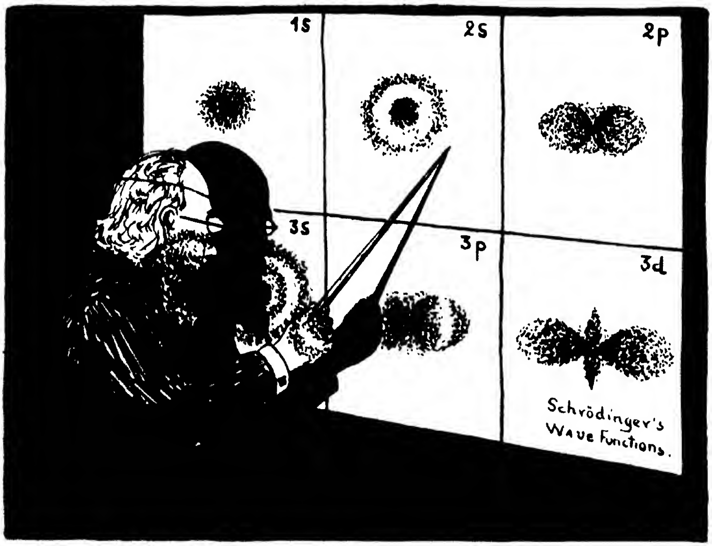
at *any* distance from the nucleus and puts *no restriction* on the eccentricity (i.e. elongation) of its orbit, the selected orbits of Bohr's theory form a discrete set with all their characteristic dimensions sharply defined. Numbers and letters standing near each orbit indicate the name of any given orbit in the general classifications; you may notice, for example, that larger numbers correspond to the orbits of larger diameters.

Although Bohr's theory of atomic structure turned out to be extremely fruitful in the explanation of various properties of atoms and molecules, the fundamental notion of discrete quantum orbits remained rather unclear, and the deeper we tried to go into the analysis of this unusual restriction of classical theory, the less clear was the entire picture.

It finally became clear that the disadvantage of Bohr's theory lay in the fact that, *instead of changing* classical mechanics in some fundamental way, it *was simply restricting* the results of this system by additional conditions which were in principle foreign to the whole structure of classical theory. The correct solution of the entire problem came only thirteen years later, in the form of so-called *"wave-mechanics"*, which has modified the entire basis of classical mechanics in accordance with the new quantum-principle. And, in spite of the fact that at first sight the system of wave-mechanics may seem still crazier than Bohr's old theory, this new micro-mechanics represents one of the most consistent and accepted parts of the theoretical physics of today. Since the fundamental principle of the new mechanics, and in particular the notions of *"indeterminacy"* and *"spreading out trajectories"*, have been already discussed by me in one of my previous lectures,[2] I will refer

[2] The professor refers here to his lecture *"Quantum of Action"* given during the previous academic year, and published in the book *Mr Tompkins in Wonderland* by Cambridge University Press and The Macmillan Co., 1940.

you to your memory or your notes, and will return to the problem of atomic structure. In the diagram which I project now (Second plate, please!) you see the way in which the motion of atomic electrons is visualized by wave-mechanical theory from the point of view of "spreading out trajectories". This picture represents the same types of



motion as those represented classically in the previous diagram (apart from the fact that for technical reasons each type of motion is now drawn separately), but instead of the sharp-lined trajectories of Bohr's theory, we have now diffuse patterns consistent with the fundamental *uncertainty principle.* The notations of different states of motion is the same as on the previous diagram, and, comparing the two, you will notice, if you will stretch your imagination slightly, that our cloudy

form repeats rather faithfully the general features of the old Bohr's orbits.

These diagrams show you quite clearly what happens to the good old-fashioned trajectories of classical mechanics when the quantum is at play, and although a layman might think it a fantastic dream, scientists working in the microcosmos of atoms do not experience any difficulties in accepting this picture.

After this short survey of the possible states of motion in the electronic atmosphere of an atom, we now come to an important problem concerning the distribution of various atomic electrons among various possible states of motion. Here again we encounter a new principle, a principle quite unfamiliar in the macroscopic world. This principle was first formulated by my young friend WOLFGANG PAULI, and states that *in the community of electrons of a given atom no two particles may simultaneously possess the same type of motion.* This restriction would be of no great importance if, as it is in classical mechanics, there were an infinity of possible motions. Since, however, the numbers of "permitted" states of motion is drastically reduced by the quantum-laws, the Pauli-principle plays a very important role in the atomic world: it secures a more or less uniform distribution of electrons around the atomic nucleus and prevents them from crowding in one particular spot.

You must not conclude, however, from the above formulation of the new principle that each of the diffuse quantum-states of motion represented on my diagram may be "occupied" by one electron only. In fact, quite apart from the motion along its orbit, each electron is also spinning around its own axis, and it will not distress Dr Pauli at all if two electrons move along the same orbit, provided they spin in different directions. Now the study of electron spin indicates that the velocity of their rotation around their own axis is always the same, and that the

direction of this axis must always be perpendicular to the plane of the orbit. This leaves only two different possibilities of spinning, which can be characterized as *"clockwise"* and *"counter-clockwise"*.

Thus the Pauli-principle as applied to the quantum-states in an atom can be reformulated in the following way: *each quantum state of motion can be "occupied" by not more than two electrons, in which case the spins of these two particles must be in opposite directions.* Thus, as we proceed along the natural sequence of elements toward the atoms with a larger and larger number of electrons, we find different quantum-states of motion being gradually filled with the electrons, and the diameter of the atom steadily increases. It must also be mentioned in this connection that, from the point of view of the strength of their binding, different quantum-states of atomic electrons can be united in separate groups (or shells) of states with approximately equal binding. When we proceed along the natural sequence of elements, one group is filled after another, and, as a consequence of their subsequent filling of electronic shells, the properties of the atoms also change periodically. This is the explanation of the well-known periodic-properties of elements, discovered empirically by the Russian chemist DIMITRIJ MENDELEÉFF.

Third Lecture[1]

HOLES IN NOTHING

Ladies and Gentlemen:

Tonight I will request your special attention, since the problems which I am going to discuss are as difficult as they are fascinating. I am going to speak about new particles, known as "positrons", possessing more than unusual properties. It is very instructive to notice that the existence of this new kind of particle was predicted on the basis of purely theoretical considerations several years before they were actually detected, and that their empirical discovery was largely helped by the theoretical preview of their main properties.

The honor of having made this prediction belongs to a young British physicist, PAUL ADRIEN MAURICE DIRAC, who arrived at his conclusions on the basis of theoretical considerations so strange and fantastic that most physicists refused to believe them for quite a long time. The basic idea of Dirac's theory can be formulated in these simple words: *"There should be holes in empty space."* I see you are surprised; well, so were all physicists when Dirac uttered these significant words. How can there be a hole in an empty space? Does this make any sense? Yes, if one implies that the so-called empty space is actually not so empty as we believe it to be. And, in fact, the main point of Dirac's theory consists in the assumption that *the so-called empty space, or vacuum, is actually thickly populated by an infinite number of ordinary negative electrons packed together in a very regular and uniform way.* It is need-

[1] **Note by the editor: Mr Tompkins did not go to this lecture, as his father-in-law advised him in advance that it would be well over his head. Maybe he was right.**

less to say that such an odd hypothesis did not come to Dirac's mind as the result of sheer fantasy, but that he was more or less forced to it by a number of considerations pertaining to the theory of ordinary negative electrons. In fact, the theory leads to an inevitable conclusion that besides the quantum-states of motion in atoms, there is also an infinite number of special "negative quantum-states" belonging to a pure vacuum, and that, unless one prevents electrons from going over into these "more comfortable" states of motion, they will all abandon their atoms and will be, so to speak, dissolved into empty space. Since furthermore, the only way of preventing an electron from going where it pleases, is to have this particular spot "occupied" by some other electron (remember Pauli), one must have *all* these quantum-states in vacuum completely filled up by an infinity of electrons distributed uniformly through the entire space.

I am afraid that my words sound like some kind of scientific abracadabra, and that you cannot make head or tail of all this, but the subject is really very difficult, and I can only hope that if you keep on listening attentively you will be able finally to get some idea about the nature of Dirac's theory.

Well, one way or another, we have arrived at the conclusion that empty space is thickly filled with electrons, distributed with a uniform but infinitely high density. How does it happen that we do not notice them at all, and consider the vacuum as an absolutely empty space?

You may understand the answer if you will put yourself in the position of a deepwater fish suspended in the ocean. Does the fish, even if it is intelligent enough to put such a question, realize that it is surrounded by water? Not necessarily, since the water around it is quite uniform and extends seemingly beyond any limit in all directions. In fact, if there were no friction, which by the way enables the fish to move

through the water, the fish could very well imagine itself to be suspended in an absolute vacuum. Well, in the case of Dirac's electron-ocean, which is also quite uniform and extends indefinitely in all directions, the friction *is* absent, and we find ourselves in the position of the fish having no idea of the material medium which surrounds it. In comparing Dirac's electron-ocean with the ordinary ocean we must however make one important exception, in order not to be carried too far by this analogy. The point is that, since the electrons forming Dirac's ocean are subject to the Pauli-principle, not a single electron can be added to this ocean when it is completely full. A new electron beyond this limit will be unable to find any place in the continuous distribution, and will remain above it, much the same as an extra orange on the top of a closely packed crate in a grocery store. Such a surplus electron due to the "overflow" of Dirac's ocean will retain its individuality of an isolated particle, and according to Dirac, that is the only kind of electron which we can observe in our physical experiments. You may say that the physical reality belongs only to the occasional splashes rising above the surface, whereas the main body of water remains completely unobservable.

So where are we now? We have introduced with much difficulty the notion of this fantastic electron-ocean, and then have done our best to show that it cannot ever be observed. What is the use of it all? Well, let us turn again to our fish suspended in the depths of the ocean and let us suppose that it observes a group of air-bubbles rising past it towards the surface. What do you suppose the fish will think?

"It would think that somebody has been drowned," suggested a cheerful voice from a back bench.

I don't consider that a very clever remark, especially when we are discussing such a serious problem! Why, the fish will, of course, think

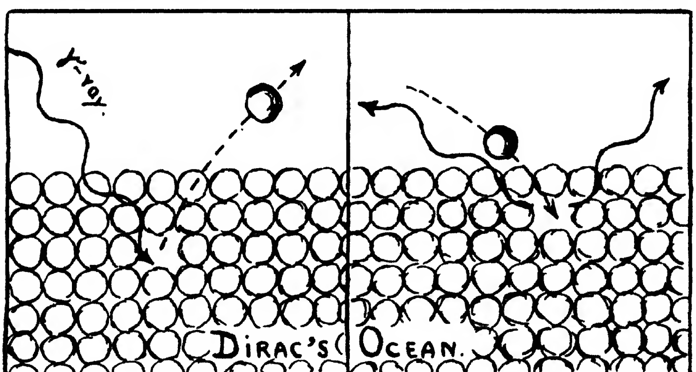
that it observes a very unusual phenomenon. It will wonder why the forces of gravity, which customarily pull everything downwards, are pushing these glittering little spheres in an exactly opposite direction. And it would take a master mind to explain to an ordinary fish that nothing is wrong with gravity, and that *the bubbles being only holes in the water, move up only because the gravity pulls down the surrounding particles of water.* Not being aware of the existence of water around it, and not even having a proper word for it in its fishy language, many a fish would declare this explanation to be completely insane.

If you now replace the ordinary body of water by Dirac's electronic frictionless ocean, and put yourself in the position of the fish observing rising bubbles, you will get a pretty clear idea as to the nature of this new particle the positron. In fact, if by some means we succeed in removing one of the electrons from the Dirac ocean, there will remain the "hole" which, owing to the lack of a negative charge, will be observed as a positively charged particle. This hole could be filled up by one of the neighboring electrons belonging to the continuous distribution, but in this case the place previously occupied by that electron will remain vacant. In this way the hole will move from place to place, and, noticing it as something lacking uniformity in the unobservable continuous distribution, we will be apt to consider it as a real material particle, carrying a positive electric charge.

But let us see what happens when such a traveling hole encounters a surplus electron looking for a "comfortable place" in Dirac's ocean.

It is clear that, as the result of such an encounter, the surplus electron will inevitably fall into the hole, filling it up, and the surprised physicist observing the process will register the phenomenon as *the mutual annihilation* of a positive and a negative electron. The energy set free in the fall will be emitted in the form of short wave radiation, and will represent the only remainder of two electrons who have eaten each other up like the two wolves in the well-known children's story.

But one can also imagine a reverse process in which a pair consisting of a negative and a positive electron are "created from nothing" by the action of a powerful external radiation. From the point of view of Dirac's theory, such a process consists simply in kicking out an electron from the continuous distribution, and should be considered actually not as a "creation" but rather as a separation of two opposite electric charges. In the diagram which I now show you, these two processes of electronic "creation" and "annihilation" are represented in a very crude schematic way, and you see that there is nothing mysterious about



Creation of pair *Annihilation of pair*

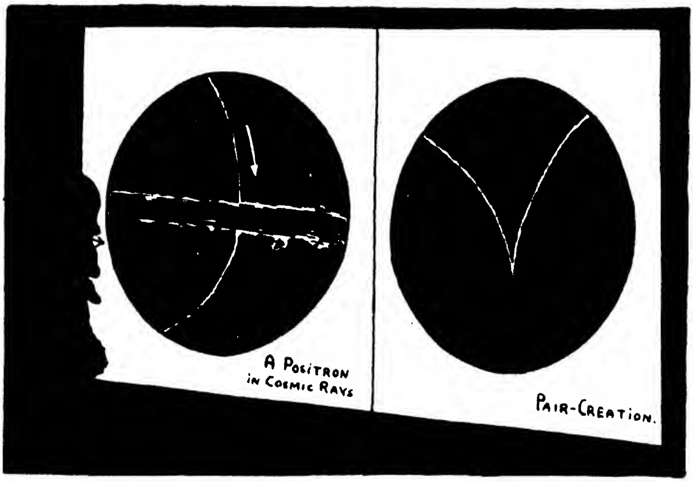
the matter. I must add here that, although strictly speaking the process of pair-creation may take place in an absolute vacuum, its probability would be extremely small; you may say that the electron-distribution of a vacuum is too smooth to break it up. On the other hand, in the presence of heavy material particles, which serve as the point of support for the gamma-ray digging into the electronic-distribution, the probability of pair-creation is largely increased and it can be easily observed.

It is clear however that positrons created in the way described above will not exist very long and will soon be annihilated in an encounter with one of the negative electrons which possess large numerical superiority in our corner of the universe. This fact constitutes the reason for the comparatively late discovery of these interesting particles. In fact, the first report on positive electrons was made only in August 1932 (Dirac's theory was published in 1930), by the Californian physicist CARL ANDERSON who, in his studies of cosmic radiation, found particles which resembled in all their aspects ordinary electrons with the only important difference that instead of a negative electric charge they carried a positive one. Soon after this we learned a simple way of producing electron pairs under laboratory conditions by sending a powerful beam of high-frequency radiation (radioactive gamma rays) through any kind of material substance.

On the next plate I am going to show you, you will see the so-called "cloud-chamber photographs" of the cosmic-ray positrons, and of the process of pair-creation itself. But before doing so I must explain the way in which these photographs were obtained. The cloud-, or Wilson-chamber, is one of the most useful instruments of modern experimental physics, and it is based on the fact that any electrically charged particle moving through a gas produces a large number of ions along its track. If the gas is saturated with water vapors, tiny droplets of water will

condense on these ions, thus forming a thin layer of fog extending all along the track. Illuminating this foggy band by a strong beam of light on a dark background, we obtain perfect pictures, showing all the details of motion.

The first of the two pictures now projected on the screen is the original photograph by Anderson of a cosmic-ray positron, and is, by the



way, the first picture of this particle ever taken. The broad horizontal band going across the picture is a thick lead plate placed across the chamber, and the track of the positron is seen as a thin curved scratch going through the plate. The track is curved because during the experiment the cloud-chamber was placed in a strong magnetic field influencing the motion of the particle. The lead plate and magnetic field were employed in order to determine the sign of the electric charge carried

by the particle, which can be done on the basis of the following argumentation. It is known that the deflection of the trajectory produced by the magnetic field depends on the sign of the charge of the moving particle. In this particular case the magnet was placed in such a way that negative electrons would be deflected to the left of the original direction of their motion, whereas positive electrons would be deflected to the right. Thus if the particle in the photograph was moving upwards it may have had a negative charge. But how to tell which way it was moving? That is where the lead plate comes in. After crossing the plate the particle must have lost some of its original energy, and hence the bending effect of the magnetic field must be larger. In the present photograph the track is bent more strongly *under* the plate (it can hardly be seen at first glance, but comes out in the measurement of the plate). Consequently the particle was moving downwards, and its charge was positive.

The other photograph was taken by JAMES CHADWICK at the University of Cambridge and represents the process of pair creation in the air of the cloud-chamber. A strong gamma-ray entering from below, and producing no visible track in the photograph, produced an electronic pair in the middle of the chamber, and the two particles are flying apart, being deflected in opposite directions by the strong magnetic field. Looking at this photograph you may wonder why the positron (which is on the left) is not annihilated on its way through the gas. The answer to this question is also given by Dirac's theory and will be easily understood by anyone who plays golf. If, in putting on the green, you hit the ball too hard, it will not fall into the hole even if your aim is true. In fact a rapidly moving ball will simply jump over the hole and roll on. In the very same way a fast moving electron will not fall into Dirac's hole until its velocity is considerably reduced. Thus a positron

has a better chance of being annihilated at the end of its trajectory when it is slowed down by collision along the track. And, as a matter of fact, careful observations show that the radiation which accompanies any annihilation process is actually present at the end of the positron's trajectory. This fact represents an additional confirmation of Dirac's theory.

There remain now two general points still to be discussed. First of all I have been referring to negative electrons as the overflow of Dirac's ocean and to positrons as the holes in it. One can, however, reverse the point of view and consider ordinary electrons as the holes, giving to positrons the role of thrown out particles. To do this we have only to assume that Dirac's ocean is not overflowing, but that on the contrary, there is always a shortage of particles. In such a case we can visualize Dirac's distribution to be something like a piece of Swiss cheese with a lot of holes in it. Owing to the general shortage of particles the holes will exist permanently, and if one of the particles is thrown out of distribution it will soon fall back again into one of the holes. It should be stated, however, that both pictures are absolutely equivalent from physical as well as mathematical points of view, and there is actually no difference no matter which one we choose.

The second point can be put in the form of the following question: "If in the part of the world in which we live there is a definite preponderance in the number of negative electrons, are we to suppose that in some other parts of the Universe this is reversed?" In other words, is the overflow of Dirac's ocean in our neighborhood compensated for by the lack of these particles somewhere else?

This extremely interesting question is a very hard one to answer. In fact, since atoms built by positive electrons rotating around negative nuclei would have exactly the same optical properties as ordinary atoms,

there is no way to decide this question by any spectroscopic observation. For all that we know, it is quite possible that the material forming, let us say, the Great Andromeda Nebula is of this topsy-turvy type, but the only way to prove it would be to get hold of a piece of that material and see whether or not it is annihilated by contact with terrestrial materials. There would be a terrible explosion, of course! There has recently been some talk about the possibility that certain meteorites exploding in the terrestrial atmosphere are formed of this topsy-turvy material, but I don't think that much credit should be given to it. In fact it may very well be that this question of the overflow and draught of Dirac's ocean in different parts of the Universe will remain unanswered forever.

Fourth Lecture [1]

THE WORLD INSIDE THE NUCLEUS

Ladies and Gentlemen:

Digging deeper and deeper into the structure of matter, we will now try to penetrate with our mental eye into the interior of the atomic nucleus, the mysterious region occupying only one thousand billionth part of the total volume of the atom itself. Yet, in spite of the almost incredibly small dimensions of our new field of investigation we shall find it full of very animated activity. In fact, the nucleus is after all the heart of the atom, and, in spite of its relatively small size, contains about 99.97 percent of total atomic mass.

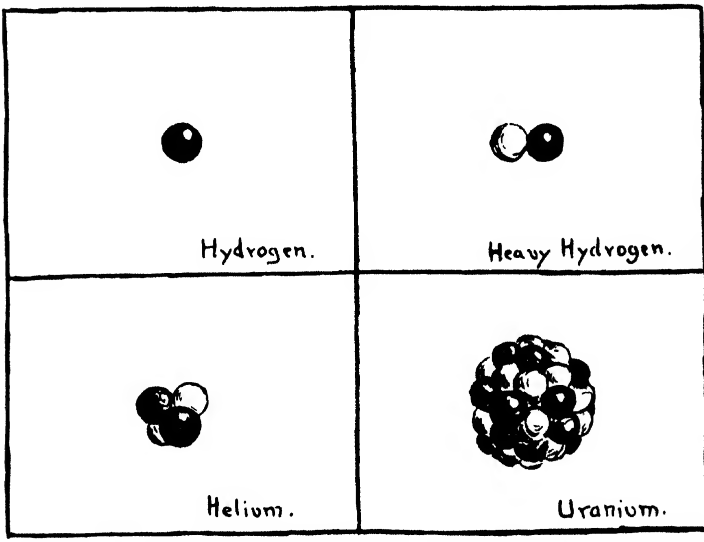
Entering the nuclear region from the thinly populated electronic atmosphere of the atom, we shall be surprised at once by the extremely overcrowded state of the local population. Whereas electrons of atomic atmosphere move, on the average, distances exceeding by a factor of several hundred thousand their own diameters, the particles living inside the nucleus would literally be rubbing elbows with one another, if only they had elbows. In this sense the picture represented by the nuclear interior is very similar to that of an ordinary liquid, except that instead of molecules we encounter here much smaller and also much more elementary particles known as *protons* and *neutrons*. It may be noticed here that, in spite of having different names, protons and neu-

[1] Note by the editor: This is the last lecture Mr Tompkins attended before he was struck by a high tension spark during a visit to his father-in-law's laboratory.

trons are now considered simply as two different electric states of the same elementary heavy particle known as the "nucleon". Proton is a positively charged nucleon, neutron is an electrically neutral nucleon, and the possibility is not excluded that there are also negative nucleons, although as yet they have never been observed. As far as their geometrical dimensions are concerned, nucleons are not very different from electrons, possessing a diameter of about .0000000000001 centimeters. But they are much heavier, and a proton or neutron would tip the scales against eighteen hundred and forty electrons. As I have said, the particles forming the atomic nucleus are packed very close together, and this is due to the action of certain special *nuclear cohesive forces,* similar to those acting between the molecules in a liquid. And, just as in liquids, those forces, while preventing the particles from being completely separated, do not hinder their displacement relative to one another. Thus nuclear matter possesses a certain degree of fluidity, and not being disturbed by any external forces, assumes the shape of a spherical drop, just like an ordinary drop of water. In the schematic diagram which I am going to show you now (The plate, please!), you see different types of nuclei built from protons and neutrons. The simplest is the nucleus of hydrogen which consists of just one proton, whereas the most complicated Uranium nucleus consists of ninety-two protons and one hundred and forty-two neutrons. Of course, you must consider these pictures only as a highly schematic presentation of the actual situation, since, owing to the fundamental uncertainty principle of the quantum theory, the position of each nucleon is actually "spread out" over the entire nuclear region.

As I have said, particles forming an atomic nucleus are held together by strong cohesive forces, but apart from these attractive forces there are also forces of another kind acting in the opposite direction. In fact,

protons, which form about one half of the total nuclear population, carry a positive electric charge, and are consequently repelled from one another by the Coulomb electrostatic forces. For the light nuclei, where the electric charge is comparatively small, this Coulomb repulsion is of



no consequence, but in the case of heavier, highly charged nuclei Coulomb forces begin to offer serious competition to the attractive cohesive forces. When this happens, the nucleus is no longer stable, and is apt to eject some of its constituent parts. That is exactly what happens to a number of elements located at the very end of the periodic system, known as "*radioactive elements*".

From the above considerations you might conclude that these heavy unstable nuclei should emit protons, since neutrons do not carry any

electric charge and are therefore not subject to the Coulomb repulsive forces. Experiments show us, however, that the particles actually emitted are the so-called *alpha-particles* (helium-nuclei), i.e. complex particles built of two protons and two neutrons each. The explanation of this fact lies in the specific grouping of nuclear constituent parts. It appears that the combination of two protons and two neutrons, forming an alpha-particle, is especially stable, and it is therefore much easier to throw the whole group out at once than to break it into separate protons and neutrons.

As you probably know, the phenomenon of radioactive decay was first discovered by the French physicist HENRI BECQUEREL, and its interpretation as the result of spontaneous disintegration of atomic nuclei was given by the famous British physicist LORD RUTHERFORD, whose name I have already mentioned several times before in other connections, and to whom science owes so great a debt for important discoveries in the physics of the atomic nucleus.

One of the most peculiar features of the process of alpha-decay consists in the sometimes extremely long periods of time needed by alpha-particles in order to make their "getaway" from the nucleus. For *Uranium* and *Thorium* this period is measured by billions of years; for *Radium* it is about sixteen centuries, and although there are some elements in which decay takes place in a fraction of a second, their life-span can also be considered very long as compared with the rapidity of intra-nuclear motion.

What is it that forces an alpha-particle to stay sometimes for many billions of years inside the nucleus? And if it has already stayed so long why does it finally get out?

To answer this question we must first learn a little more about the comparative strength of the cohesive forces of attraction, and the elec-

trostatic forces of repulsion acting on the particle on its way out of the nucleus. A careful experimental study of these forces was made by Rutherford, who used the so-called *"atomic bombardment"* method. In his famous experiments at the Cavendish Laboratory, Rutherford directed a beam of fast moving alpha-particles, emitted by some radioactive substance, and observed the deviations (scattering) of these atomic projectiles resulting from their collisions with the nuclei of the bombarded substance. These experiments confirmed the fact that, while at great distances from the nucleus the projectiles are strongly repelled by electric forces of nuclear charge, this repulsion changes into a strong attraction if the projectile manages to come very close to the outer limits of the nuclear region. You can say that the nucleus is somewhat analogous to a fortress surrounded on all sides by a high, steep bulwark, preventing the particles from getting in as well as from getting out. But the most striking result of Rutherford's experiments consists in the fact that *the alpha-particles getting out of the nucleus in the process of radioactive decay, as well as the projectiles which penetrate into the nucleus from outside, possess actually less energy than would correspond to the top of the bulwark, or the "potential barrier" as we usually call it.* This was the fact which stood in complete contradiction to all the fundamental ideas of classical mechanics. Indeed, how can you expect a ball to roll over a hill if you have thrown it with far less energy than is necessary to get to the top of the hill? Classical physics could only open its eyes very wide, and suggest that there must have been some mistake in Rutherford's experiments.

But, as a matter of fact, there was no mistake, and if someone was in error it was not Lord Rutherford but classical mechanics itself. The situation was clarified simultaneously by my good friend DR GEORGE GAMOW and by DRS RONALD GURNEY and E. U. CONDON, who pointed

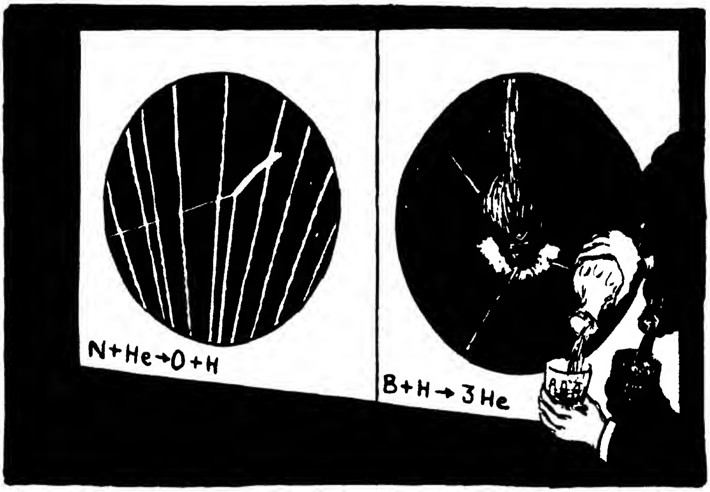
out that there is no difficulty whatsoever if one looks at the problem from the point of view of modern quantum theory. In fact, we know that quantum physics today rejects the well defined linear trajectories of classical theory, and replaces them with diffuse ghostly trails. And, just as a good old-fashioned ghost could pass without difficulty through the thick masonry walls of an old castle, these ghostly trajectories can penetrate through potential barriers which seem to be quite impenetrable from the classical point of view.

And please do not think I am joking; the penetrability of potential barriers for particles with insufficent energy comes as a direct mathematical consequence of the fundamental equations of the new quantum mechanics, and represents one of the most important differences between the new and old ideas about motion. But, although the new mechanics permits such unusual effects, it does so only with strong restrictions: in most cases the chances of crossing the barrier are extremely small, and the imprisoned particle must throw itself against the wall an almost incredible number of times before its attempt finally succeeds. The quantum theory gives us exact rules concerning the calculation of the probability of such an escape, and it has been shown that the observed periods of alpha-decay are in complete agreement with the expectation of the theory. Also in the case of projectiles which are shot into the nucleus from the outside, the results of quantum-mechanical calculations are in very close agreement with the experiment.

Before going any further, I want to show you some photographs representing the process of disintegration of various nuclei which were hit by high energy atomic projectiles. (Next plate, please!)

In this plate you see two different disintegration processes photographed in the cloud-chamber which I have described to you in a previous lecture. The picture on the left shows a nitrogen nucleus struck

by a fast alpha-particle, and is the first picture of artificial transmutation of elements ever taken. It was made by DR PATRICK BLACKETT, a pupil of Lord Rutherford. You see a large number of alpha tracks radiating from a powerful alpha-ray source which is not shown in the picture. Most of these particles are passing through the field of vision



without a single serious collision, but one of them has just succeeded in hitting a nitrogen nucleus. The track of the alpha particle stops right there, and you can see two other tracks coming out from the collision point. The long thin track belongs to a proton kicked out from the nitrogen nucleus, whereas the short heavy one represents the recoil of the nucleus itself. This isn't, however, a nitrogen nucleus any more, since by losing a proton and absorbing the incidental alpha particle it has been transformed into a nucleus of oxygen. Thus we have here an

alchemic transformation of nitrogen into oxygen with hydrogen as a by-product

The second photograph corresponds to nuclear disintegration by the impact of an artificially accelerated proton. A fast beam of protons is being produced in a special high-tension machine, known to the general public as an *"atom-smasher"*, and enters the chamber through a long tube, the end of which is seen in the photograph. The target, in this case a thin layer of Boron, is placed at the lower opening of the tube so that nuclear fragments produced in the collision must pass through the air in the chamber, producing cloudy tracks. As you see from the picture, the nucleus of Boron, being hit by a proton, breaks into three parts, and counting the balance of the electric charges, we come to the conclusion that each of these fragments is an alpha particle, i.e. a helium-nucleus. The two transformations shown in the photographs represent rather typical examples of several hundred other nuclear transformations studied in experimental physics today. In all transformations of this kind, known as *"substitutional nuclear reactions"* the incidental particle, (proton, neutron or alpha particle) penetrates into the nucleus, kicks some other particle out, and remains itself in its place. We have the substitution of a proton by an alpha particle, of alpha particle by proton, proton by neutron etc. In all such transformations the new element formed in the reaction represents a close neighbor of the bombarded element in the periodic system.

But only a few years ago, in fact just before the war broke out, two German chemists O. HAHN and F. STRASSMANN discovered an entirely new type of nuclear transformation, in which *a heavy nucleus breaks in two equal parts with the liberation of a tremendous amount of energy.* This phenomenon, known as *"nuclear fission"* was noticed first in the case of Uranium bombarded by a beam of neutrons, but it was soon

found that other elements also located near the end of the periodic system possess similar properties. It seems, indeed that these heavy nuclei are already at the limit of their stability, and that the smallest provocation, caused by a collision with a neutron, is enough to make them break into two, like an oversized drop of mercury. The fact of such instability of heavy nuclei throws light on the question as to why there are only ninety-two elements in nature; in fact any nucleus heavier than Uranium could not exist for any period of time and would immediately break into much smaller fragments. The phenomenon of "nuclear fission" is also interesting from the practical point of view, since it opens up certain possibilities for the utilisation of nuclear energy. The point is that, breaking in half, heavy nuclei also eject a number of neutrons which may cause the fission of neighboring nuclei. This may lead to an explosive reaction in which all the energy stored inside the nuclei will be set free in a fraction of a second. And, if you remember that the nuclear energy contained in one pound of Uranium is equivalent to the energy content of ten tons of coal, you will understand that the possibility of liberating this energy would produce very important changes in our economy. However it is not an easy task to create the conditions necessary for such an explosive process, and it is very difficult to say whether the solution of this problem can be expected within a year, a decade, or a century.

We have gone as far as this without yet mentioning the second type of nuclear transformation known as the process of *"beta-decay"*, and consisting of the emission by the nucleus of an ordinary negative, or a positive electron. You may remember that when I spoke, at the beginning of this lecture, about the particles constituting the nucleus, I mentioned protons and neutrons, but no electrons. Well, that is quite right, there are no electrons in the nucleus; and still they are emitted by the

nucleus in quite a number of different reactions. The explanation of this apparent paradox lies in the fact that the particles known as electrons can be "created" or "born" in space if only a sufficient electric charge is available. The situation is somewhat similar to Dirac's "pair-creation" described in my previous lecture, but with this difference, that instead of the formation of two electrons (positive and negative) with mutually compensating charges, we have to deal here with the formation of one electron only, the charge being taken from the heavy nucleon. If, for example, a nuclear proton chooses to turn into a neutron, its positive electric charge will be set free and will be thrown out of the nucleus in the form of a positive electron. In the reverse process in which a neutron adopts a positive charge, thus becoming a proton, the compensating electric charge will be set free in the form of a negative electron.

But even in this case when only one electron is "born" to the nucleus, it is not born entirely alone. In fact, we believe now that the birth of a single electron (positive or negative) is always accompanied by the simultaneous "birth" of another particle, and a very strange particle it is indeed! Its discoverer, DR PAULI (of "Pauli-principle" fame) called it *"neutrino"*, and endowed it with a number of very peculiar properties. The neutrino has no electric charge, no ponderable mass, and possesses almost unlimited penetrating power; in fact, according to the present view, a neutrino can penetrate without much difficulty through a solid wall of iron many millions of miles thick. It is no wonder that no one has yet succeeded in catching this particle, or in locking it up. You can ask me, of course, what is the sense in introducing a notion of a particle which has nothing, and cannot be tackled in any way! Well, there is definite sense in it: and it was actually done in order to account for certain energy losses in nuclear reactions, losses which were definitely es-

tablished by experiment but could not be accounted for in any conceivable way. If you see money periodically disappearing from your pocket, and if the most skillful detectives fail to catch the thief, you may gradually come to the conclusion that some uncatchable master-thief is at work. And this is exactly the role for which the notion of the "neutrino" was introduced. But since they were first introduced to science, these "thieves of Baghdad of nuclear physics" have succeeded in establishing themselves rather solidly, and only recently it was proposed that the huge and violent stellar explosions, known in astronomy as *"Super-nova-phenomena"*, may be due to the loss of energy from the stellar interior as a consequence of a large scale neutrino emission.

The presentation of this lecture would not be complete without mentioning the newest type of nuclear particles, introduced by the Japanese physicist YUKAVA, and known at present as *"mesons"*. These particles, possessing an intermediate mass between protons and electrons (180 electron masses, or 1/10 of a proton mass), were primarily intended as an explanation of cohesive forces holding the nucleus together, and served, so to speak, as a kind of *"nuclear glue"*. For quite a while the hypothesis of "mesons" was not in favor among nuclear physicists, but recently, after these particles had actually been found in cosmic rays, they have taken quite a prominent position. We do not know, though, whether the *"meson"* should be considered as a really elementary particle, and it is quite possible that it represents a close-quarter combination of an electron and a neutrino.

Well, I think I have given you quite enough material now to give you bad dreams for the rest of the week, and so I will wish you all a very good night.